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USAAVLABS TECHNICAL REPORT 67-6

IMPROVED CRASH-RESISTANT FUEL CELL MATERIAL

By

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April 1967

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DA 44-177-AMC-347(T)
GOODYEAR AEROSPACE CORPORATION
LITCHFIELD PARK, ARIZONA

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FORT EUSTIS, VIRGINIA 23604

This report was prepared by Goodyear Aerospace Corporation, Arizona Division, Litchfield Park, Arizona, under the terms of Contract DA 44-177-AMC-347(T).

This effort consisted of the investigation, through dynamic testing, of the factors which must be considered in the design and fabrication of new materials for improved crash-resistant/self-sealing fuel cells. The data contained in this report pertain primarily to the research and test programs on crash-resistant fuel cell materials. Additional research is being conducted on the incorporation of a self-sealing capability into the crash-resistant material. Upon completion of this program, a separate report will be prepared.

Views expressed in the report have not been reviewed, or approved, by the Department of the Army; however, conclusions and recommendations contained herein are concurred in by this command.

Task 1P121401A15003

Contract DA 44-177-AMC-347(T)

USAAVLABS Technical Report 67-6

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Technical Report
GERA-1192A

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Prepared by

Goodyear Aerospace Corporation
Arizona Division
Litchfield Park, Arizona

for

U.S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

SUMMARY

Basic physical tests pertaining to Specifications MIL-T-6396 and T-27422 were performed on Goodyear Aerospace developed materials, coded ARM-018 and ARM-021. These tests were conducted first on the ARM-018 to substantiate and document the improved performance shown by this material in earlier laboratory tests and actual aircraft crashes. Material failure mechanics under a variety of static and dynamic loading conditions were included to accurately simulate and measure crash performance.

As the test series progressed, some deficiencies were discovered in the ARM-018 material. These included low dynamic puncture and tear resistance. A careful analysis of the problem area led to changes in material processing, and the resultant composition was given the code name ARM-021. Although the basic ingredients remained the same, this modification of material showed great superiority over the ARM-018 in both puncture and tear resistance.

Because of the considerable improvement of the ARM-021 material over conventional crash-resistant materials and because of deficiencies in test standards of crash resistance found in MIL-T-27422, changes in this specification have been suggested.

FOREWORD

The contractor performed all work listed herein, under provisions of Contract DA 44-177-AMC-347(T) with the U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia.

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INTRODUCTION

This report documents the design philosophy, material research, process development, and testing devoted to the fulfillment of a Government contract for improvement of crash-resistant fuel cells. The studies described in this program originated with the fuel cell research effort conducted by Aviation Safety Engineering and Research (AvSER), a division of Flight Safety Foundation, for U.S. Army Aviation Materiel Laboratories. This program was devoted to the investigation of standard and experimental cells and the determination of their resistance to rupture under controlled crash conditions. Through this effort, Goodyear Aerospace was made aware of the requirement for a fuel cell material which would be resistant to crash impacts and small arms fire. The war in Viet Nam has greatly increased the urgency of this requirement. In response to this need, Goodyear Aerospace began an accelerated company funded development program devoted to high energy absorbing plastic laminates.

Tests conducted by Goodyear Aerospace and AvSER indicated that one of the woven nylon laminates developed by Goodyear Aerospace, code ARM-018, possessed high efficiency in crash impact and puncture resistance. Actual fuel cells were fabricated using this material and were included in controlled aircraft crashes conducted by AvSER. The performance of these cells far surpassed conventional crash-resistant cells, making it apparent that better fuel containment could be achieved.

As a result of this effort, in July 1965 a research contract was awarded Goodyear Aerospace by the U.S. Army Aviation Materiel Laboratories to conduct an investigation of this material as an improved and qualified material for crash-resistant fuel cells and as a potential, self-sealing fuel cell material.

Investigation under the basic contract was limited to tests of the physical and ballistic self-sealing properties of this one material, Goodyear Aerospace code ARM-018. The standard elastomer used was a polyester polyurethane. In addition, one other polyester polyurethane and two polyether urethane elastomer systems were investigated utilizing the same reinforcement.

As a result of some deficiencies found in this basic material, a modification was introduced and bears the code name ARM-021.

Ballistic tests of the basic ARM-018 laminates generally showed good closure to hits from small arms weapons. However, to achieve a complete seal, it was necessary to apply a sealant layer. The possibility of adding a conventional gum lining to the construction was considered, but the use of coagulants appeared to

have more promise. Earlier experiments had shown that several compounds developed by Goodyear Aerospace might be used to seal quite large wounds. These compounds remained stable as low viscosity fluids until combined with hydrocarbon fuels, whereupon coagulation occurred. If the coagulant could be contained within the cell wall and fed into a wound until closure occurred, then a significant improvement in self-sealing could be obtained.

As a result of these efforts, Goodyear Aerospace was awarded an add-on contract in January 1966 for further investigation of coagulants in self-sealing tanks. Cells were made of the basic ARM-018 materials with liners capable of carrying coagulant fluids. Again the ARM-021, with coagulant carrier added, was found to be superior to the ARM-018. This coagulant-carrying modification of the ARM-021 was given the code name ARM-024.

The use of coagulants for sealing fuel cells posed several problems. First, to be practical, the coagulant would have to be limited to a single phase, thereby ruling out the possibility of the two component systems used in fuel gelation by other investigators.* The solid components of the coagulant would also have to be insoluble in the fuel to avoid gum ingestion into the system in case of internal leakage. Likewise, the solvent component of the coagulant would have to burn with the fuel without damaging the engine or changing the combustion characteristics of the fuel. The coagulant would have to be of a relatively low viscosity at all operational temperatures to permit adequate flow through a thin interstice to "feed" the bullet wound. The reacted coagulant would have to be strong enough that it would not be extruded through the wound, yet it would have to be sufficiently flexible and tenacious so that normal tank flexure from fuel surges would not work the plug loose. Low vapor pressure, high boiling point, low flammability, low reactance with the cell materials, and long-term stability were other points that had to be considered.

To meet the above requirements, it was decided that the simplest, most direct approach would be to use the following principle: a resin, or gum, which is insoluble in hydrocarbon fuels, may be dissolved in various solvents which are miscible with the hydrocarbon fuel. When these two components intermingle, the solvent is displaced by the fuel, leaving the solute as a gummy residue.

Laboratory experiments showed that several compounds would readily react in such a way. Polyvinyl chloride-cyclohexanone, acrylic methyl methacrylate (MMA) monomer, and cellulose acetate-acetone are cited as examples.

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*Eugene C. Martin, A Study of Rapid Solidification of Hydrocarbon Fuels, USATRECOM Technical Report 64-66, February 1965.

Screening tests of the various candidate solvents showed that, while many of them were miscible with the fuel and could be used as carriers for numerous polymers, most of these were impractical for one or several reasons.

Because of the time limitations set by the contractual schedule, it was necessary to use one of the coagulants as a test standard, even though long-term environmental tests might prove it to be unacceptable at some later date. Since the acrylic methyl methacrylate system showed the best all-round performance, it was chosen. Additional qualitative and environmental tests have uncovered several problems attendant to the use of the MMA coagulant. Unless properly inhibited, it will polymerize in a relatively short period of time. It also has a low flash point and has a deleterious effect on the urethane elastomers used in the ARM-024 cells. Despite these shortcomings, it appears that the use of this system in fuel cells is feasible for limited periods of time.

In designing a cell for use with coagulants, several interrelated parameters had to be considered. The ARM-021 was obviously the best material to use as a tank structure because of its high strength and tear resistance, its fluffing ability, and its internal porosity. The internal porosity would permit the coagulant fluid to flow throughout the entire cell wall, thus permitting greater fiber wetting, more instantaneous plugging, and better plug adhesion.

Early tests of various coagulant cell cores had shown that porous woven fabrics presented too great a restriction of interlaminar flow to permit satisfactory coagulant feed. An open interstice (Figure 1) would be necessary. Flow rate tests of fluted cells, using string as a skin separating device, had indicated that cells of 0.030 inch would be suitable for feeding relatively large wounds. However, ballistic tests of these fluted cells had shown inadequate crossflow, especially in cases of bullet hits tumbled parallel to the flutes. The ARM-024 cell was designed to cope with these problems.

The ARM-024 construction consists of ARM-021 material for crash resistance with a dimpled nylon film liquid coagulant carrier system and outer nonpermeable membrane added. The coagulant carrier is node bonded to the inner ply of ARM-021 and is separated from the fuel by an additional nonpermeable nylon film. Since the ARM-021 is permeable to both fuel and the liquid coagulant, a nonpermeable nylon film is bonded to the exterior ARM-021 ply. The liquid coagulant saturates the load-carrying ARM-021 dry plies in sufficient quantity to seal normal bullet wounds immediately. If additional coagulant is required to seal large wounds, it is delivered by the dimpled distribution interstice.

In designing the ARM-024 for use in a complete self-sealing system, the problem of coagulant supply requires some consideration. The most direct method of

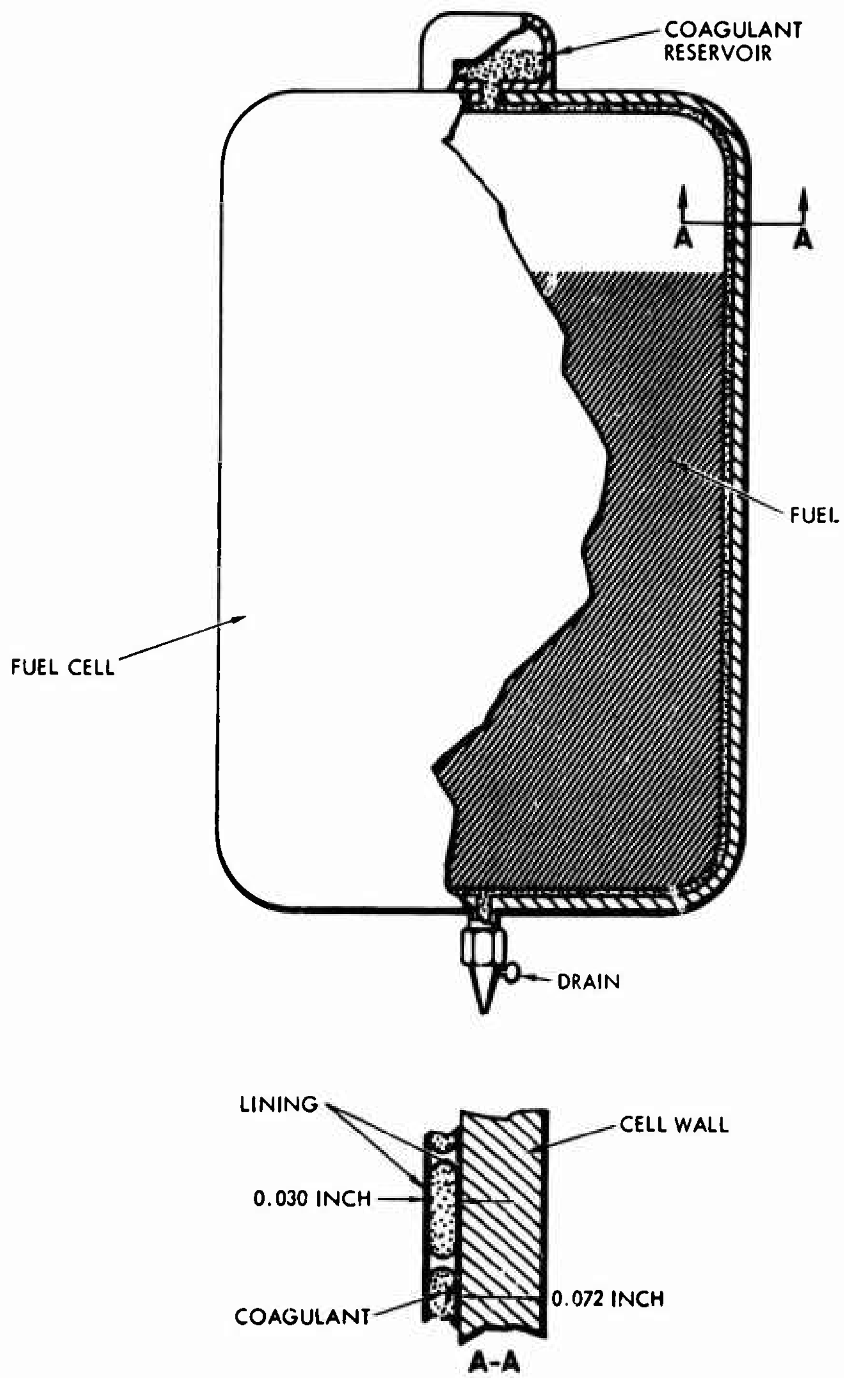

Figure 1. Basic Coagulant-Lined Fuel Cell.

keeping the cell supplied with sufficient coagulant to seal wounds is to place the reservoir on the top of the cell and permit a direct gravity feed. While this method is generally satisfactory, it does pose the problem that both internal and external coagulant leakage will occur if a hit is sustained above the fuel level. The coagulant will then drain until it reaches the level of the wound. While a small amount of internal leakage might well be tolerated, it should be avoided, if possible.

One approach which has been considered for reducing or eliminating such occurrence is to have a pressure-sensitive coagulant reservoir located at the bottom of the fuel cell. With a properly designed level control system, the coagulant would remain at a level slightly above the fuel level, eliminating unnecessary flow from hits above the fuel line.

Such a system has been studied and shows promise of success with no appreciable weight penalty. The primary problem of this method lies in the difference between the specific gravity of fuel and coagulant. The coagulant with a higher specific gravity will remain at a level lower than the fuel, unless a favorable area ratio is used to compensate for this difference. While such a system may be built without undue effort, its actual construction falls beyond the scope of this effort.

The tests of these materials generally follow the guidelines for qualitative testing set by Specifications MIL-T-6396, T-27422, P8045, and T5578. Some deviations from specification requirements were made in test procedures, and additional tests were devised in hope of gaining a broader understanding of basic failure mechanics of materials. Test emphasis was placed primarily on the construction typified by the ARM-018 and ARM-021 laminates but, to a certain extent, dealt with specimens of standard constructions. The standard cell constructions used for comparative tests are qualified for their appropriate military specifications and represent the products of three different companies.

The research program on the self-sealing coagulant and ARM-024 material has not been completed; therefore, the data contained in this report are based primarily on the results of the crash-resistant fuel cell material tests. Upon completion of the research program on the self-sealing coagulant and ARM-024 material, a separate report will be prepared.

DISCUSSION OF PROBLEM

The full-scale crash tests, performed by AvSER, along with the high incidence of post crash fire in survival aircraft crashes, have clearly demonstrated the inadequacy of current crash-resistant fuel cells. Present specifications do not reflect realistic tests nor test values to achieve adequate crash resistance.

Likewise, the materials which meet these specifications have not been designed with sufficient comprehension of the problems attendant to crash environments.

Previous investigation of this problem has indicated, both by mathematical and empirical test methods, that the burst strength and plasticity of currently accepted materials are generally inadequate.* This same investigation showed the Goodyear Aerospace ARM-018 material to be a very efficient cell material in many respects. Dynamic loading tests of various types, including actual aircraft crashes, attest to its efficiency and relative superiority over conventional cell materials. However, like its conventional counterparts, the ARM-018 uses a tightly woven nylon reinforcement (rated at 23-percent elongation at failure) bound by an elastomeric bond. Consequently, though it is superior in weight ratio when subjected to concentrated loads, it still is subject to the limited fiber reorientation which is typical of woven nylon filaments. This weakness, caused by inadequate reorientation, is not always evident. In some "survival limit" crash environments where hydraulic loading has been relatively uniform, tanks constructed of the ARM-018 material have shown very favorable results. However, in cases where sharp protrusions are combined with high hydraulic pressure and a restriction of the tank, catastrophic failure may occur at relatively low pressure levels. This weakness was accented in comparative tests between the standard ARM-018 and the MIL-T-5578 approved self-sealing cells. Impact-type puncture and tear tests showed the self-sealing materials to have a disproportionately high resistance to puncture and tear failure.

While the ARM-018 showed 80 percent greater strength (per equivalent weight of reinforcement) than the self-sealing materials, the reinforcement fibers of the self-sealing tanks showed a superiority factor of 1.5 in puncture resistance and a factor of 2.9 in impact tear resistance. The static tear resistance was nearly equal. While it is true that the additional elastomer required for the self-sealing cells may exert some influence and prohibit direct correlation of impact values, it is quite obvious that this reinforcement is a significant factor.

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*S. Harry Robertson and James W. Turnbow, Ph.D., Aircraft Fuel Tank Design Criteria, USAAVLABS Technical Report 66-24, March 1966.

One reason for this disparity in these supposedly related values apparently lies in the ability or disability of the reinforcement to deform under local impact. The unidirectional tire cord construction of the self-sealing fuel cells has little restriction to interlaminar displacement, whereas the ARM-018, in its standard form, is highly restricted. The ARM-021, because of the nonrestrictive nature of its elastomeric bond line, exhibits some interlaminar displacement and fiber reorientation. Therefore, the ARM-021 relies not only on the natural elongation of its fibrous reinforcement but also on its ability to "borrow fibers" from areas adjacent to the point of impact. As a result, it is superior to the ARM-018 laminates by the following factors: puncture resistance, 2; impact tear resistance, 1.7; and constant rate tear resistance, 1.4. While its tensile strength-tear resistance ratio is still not as impressive as the tire cord reinforced materials, its strength-weight ratio makes it superior to them by a considerable margin (Figure 2).

Another highly desirable aspect of the dynamic performance of the ARM-021 is its ability to "fluff" when hit by high-velocity projectiles. As in the case of puncture phenomena, the ability of the fibers to shift, relatively unimpeded, permits the material to be drawn into the wound locus before fiber failure occurs. The resultant mechanical closure of the wound greatly enhances the ability of a secondary sealer (such as a coagulant) to seal even large, mismatched wounds.

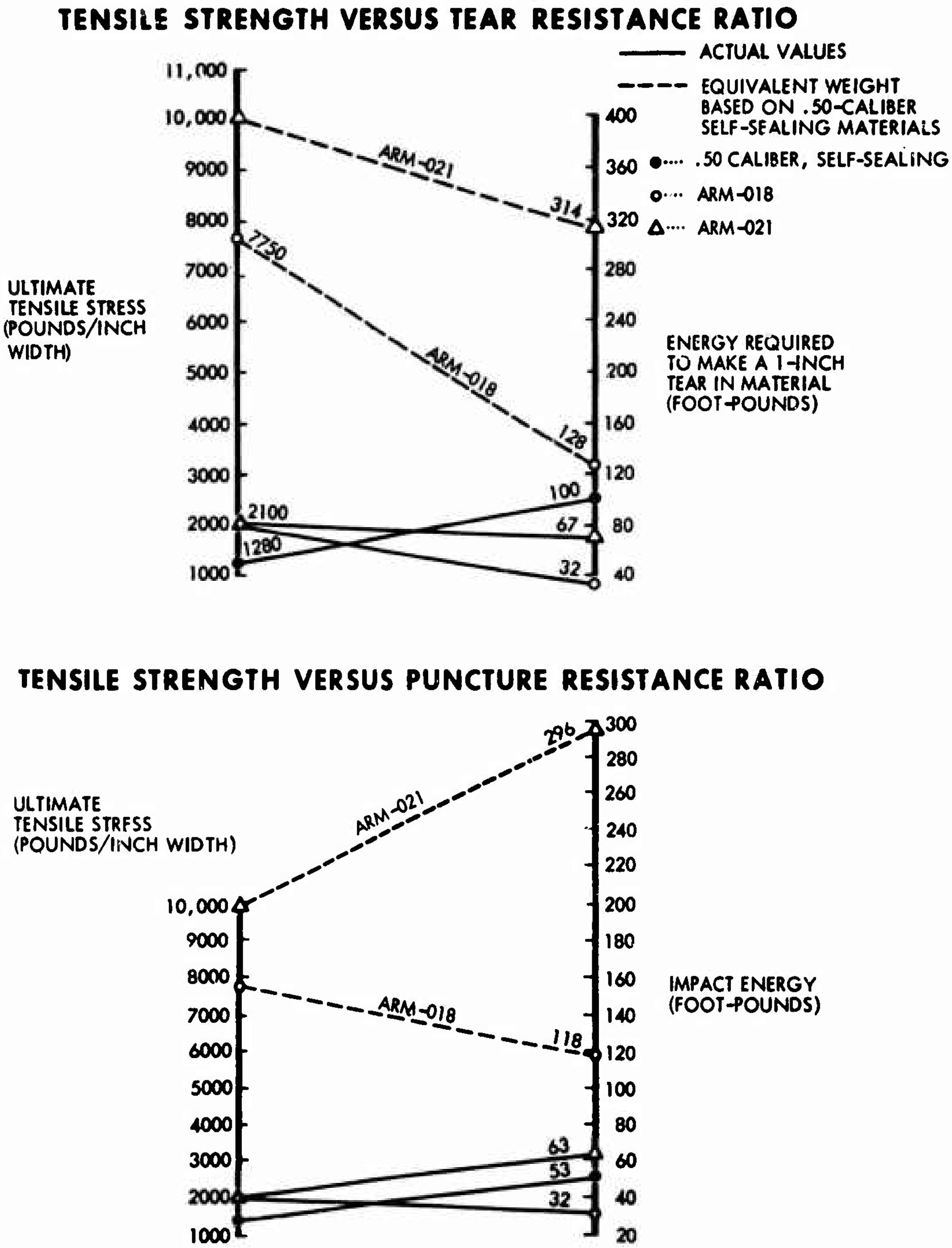

Figure 2. Strength-Energy Absorption Ratio.

DESCRIPTION OF TEST ITEM

ARM-018

The ARM-018 construction referred to in this report is a high-strength basket-weave nylon cloth of 210 denier with a thread count of 40 by 42 per inch. The fabric weight is 11.9 ounces per square yard. The standard elastomer used to laminate this cloth is a polyester polyurethane (coded W) whose properties fall generally into the following range: shore A hardness, 75; elongation, 450 percent; tensile strength, 4000 psi; and temperature range, -80 to +300 degrees F. In addition, one other polyester urethane (coded Z) and two polyether urethane elastomers (coded X and Y) were investigated using the same reinforcement.

ARM-021

The ARM-021 construction uses the same materials as ARM-018 but is processed differently. While the ARM-018 contains a high (35 to 40 percent) elastomer content, ARM-021 has a relatively low (10 to 15 percent) elastomer content. The elastomer contained in ARM-021 is primarily used for a surface bond between plies, and the reinforcement plies remain virtually dry. The ARM-021 requires an appropriate fuel barrier, such as the standard sprayed nylon and urethane combination currently used by the industry, or a urethane bonded nylon film. An outer urethane coating is also used as a fuel barrier and to prevent snagging of the fibers.

BASIC MATERIAL TESTS

TENSILE TESTS

Description

Tensile tests were conducted on single-ply samples of ARM-018 and ARM-021. Tests were conducted at temperatures of 160, 75, 0, and -65 degrees F and strain rates ranging from 0.25 to 80,000 inches per inch per minute. Stress-strain curves were recorded. The high-speed tests were conducted to simulate loading velocities experienced by fuel cells in actual crash conditions. The ultimate strengths and percentage elongation were calculated.

The high-speed tests were performed primarily on the Plas-Tech ballistic test instrument model 671 and partially on the Plastechon model 581 tester. The model 581 tester was used for purposes of data correlation and for testing at mid-range velocities. All standard-speed tensile tests were conducted on an Instron model TT-C universal test instrument.

Initial tests with cut specimens conforming to Federal Test Method Standard 406, Method 1011, showed some edge fraying with consequent erratic results. It was found that edge strands were often partially severed when the specimens were prepared. By raveling edge strands from a cut specimen until a definite number of whole strands remained, better failure modes and reproducibility were achieved.

The high-speed tensile tests were conducted to ensure that high loading rates would not appreciably alter the material performance. Tenacity strain curves of high-strength nylon generated by other investigators* have shown an increase of tenacity as the velocity of loading increased, but with lower strain values. Also, with the addition of a rate-sensitive urethane elastomer in the laminate, even greater nonuniformity in loading characteristics, as strain rate increased, would be expected.

In addition to the question of rate sensitivity at room temperature, consideration had to be given to strain-rate sensitivity at high and low temperatures. The possibility of brittle tensile failure at low temperatures and high rates appeared to be a cause for concern, especially with the ARM-018 material. Thus, the test

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*J.C. Smith, "Rapid Impact Loading of Textile Yarns," High Speed Testing, Volume I, Interscience Publishers, Inc., New York, N.Y., 1960, pp. 67-81.

series necessarily encompassed a very wide scope to ensure satisfactory performance under all conceivable conditions. Results of these tensile tests are shown in Figures 3 through 5.

Analysis of Test Results

Analysis of the tensile test results showed the following trends:

1. The material does not show a critical strain rate or a significant change in strain when tested up to 80,000 inches per inch per minute.

2. Tensile strength increases slightly as strain rate increases up to about 5,000 inches per inch per minute; above this velocity a decline occurs. Although this phenomenon is not fully understood, it is believed that the tensile modulus of the urethane elastomer may increase to such a level at high loading rates that it will exceed the modulus of the nylon reinforcement, thereby inducing early failure in a quasi-brittle mode.

3. The ultimate tensile strength of the ARM-021 construction is somewhat greater than the ARM-018. The ultimate elongation also shows an increase. Increases of both of these properties are thought to occur because of less fiber restriction resulting from the lower elastomer content of the ARM-021. The improved tensile properties are evident even at the higher loading rates (Figure 3).

AIR-GUN BURST TENSILE

Description

Burst tensile tests were performed on the ARM-018 W laminate and the standard crash-resistant material conforming to MIL-T-27422 for comparative evaluation. Tests on the ARM-021 construction were omitted because of its similarity to ARM-018 in tensile strength and because of the uniformity of load which would be expected to yield results approximating those of ARM-018. These tests were performed in accordance with Specification MIL-T-27422 requirements. The values of representative .30- and .50-caliber self-sealing materials, conforming to MIL-T-5578, are also shown for comparative purposes (Table I).

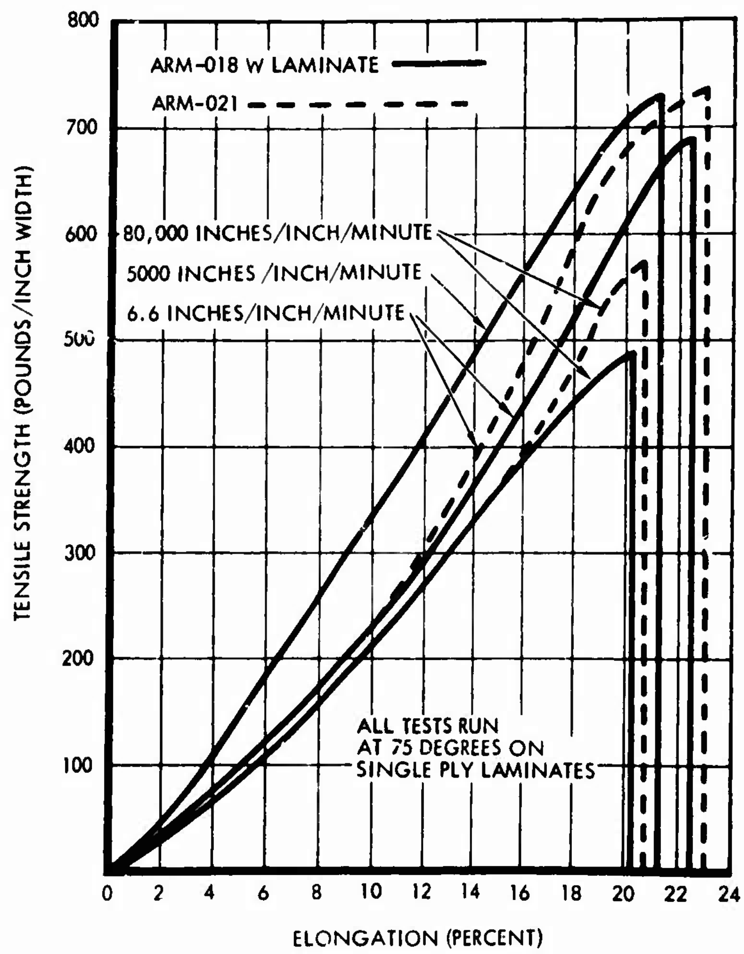

Figure 3. Typical Load-Elongation Curves at Various Loading Rates.

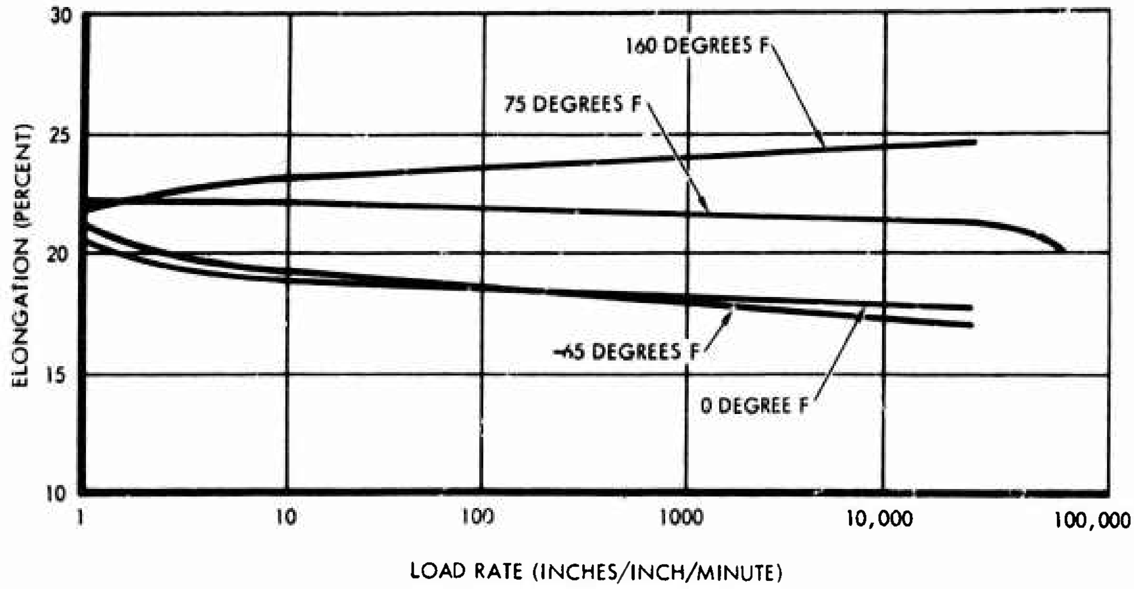

Figure 4. Elongation Versus Rate of Loading, ARM-018 W Laminate.

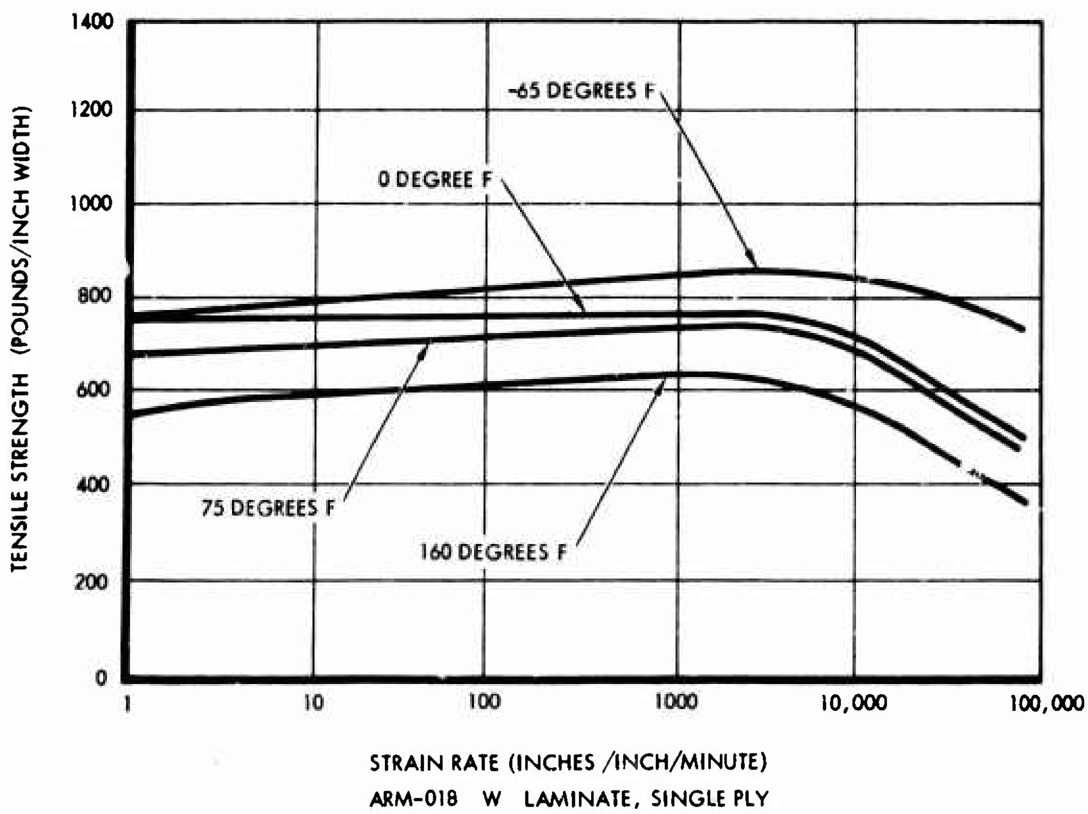

Figure 5. Tensile Rate Sensitivity.

TABLE I

AIR-GUN BURST TENSILE

Material	No. Plies	Ply Orientation	Average Elongation (Percent)	Average Ultimate Strength (Pounds/Inch)
ARM-018 W laminate	3	60 degrees	18.0	2146
ARM-018 W laminate	3	90 degrees	19.1	2103
Standard crash-resistant material*	4	90 degrees	18.7	334
Representative .30-caliber self-sealing material**	2	Bias	-	840
Representative .50-caliber self-sealing material**	3	Bias	-	1200

* Material tested by Goodyear Aerospace and other agencies for purposes of data correlation.

** Materials tested by other agencies only.

Analysis of Test Results

Problems encountered by other investigators in preventing peripheral specimen slippage and edge tearout were compounded by the very high strength of the ARM-018 laminate. The results shown are averages of the best tests of this series. In analyzing the values of the materials shown in Table I, there appears to be a very close correlation between the tensile and strain values of the burst tensile tests and the average tensile values based on single-ply fabrics tested at intermediate strain rates.

TENSILE CREEP

Description

Tensile creep tests were performed on W elastomer-impregnated, single-ply samples of ARM-018 at 0, 75, and 160 degrees F. Static loading equal to 10, 20, and 40 percent of the average ultimate material strength (based on tests at 20 inches per minute for each temperature) was applied to the samples at the specified temperatures. The test samples were raveled to nine strands in width. A suitable support structure was used, each sample being held in individual grips with a six-inch sample gage length.

Following the application of static load, dial indicators were attached to the support structure to monitor sample creep accurately. After the first day, periodic readings were made throughout the 174-day test. Figure 6 shows the results of these tests.

Analysis of Test Results

Tensile creep results were very much as anticipated. It was felt that the tensile creep properties were largely regulated by the relatively high modulus reinforcement material used, and not by the much lower modulus elastomer system. This test series therefore was limited to the ARM-018 W laminate. The resultant curves all show similar configuration - that of a gradually reduced rate of creep with time.

Because of the permanent set which occurs at all temperatures (even with only 10-percent loading), design considerations should be made accordingly, as dictated by structural demands. In cases of fuel cells supported by surrounding structure, there should be no problem.

TENSILE LAP SHEAR

Description

Lap shear adhesion tests were performed on primary bonds of ARM-018 three-ply laminates using all four elastomer systems studied. Twelve-inch-wide test panels were prepared with a 0.50-inch-wide primary bond lap running across the sample width. After the panels were cured, individual one-inch-wide test specimens were cut perpendicular to the lap. Since the ARM-021 must be lap joined with the ARM-018 type laminate, this test series includes lap shear tests of the ARM-018 only.

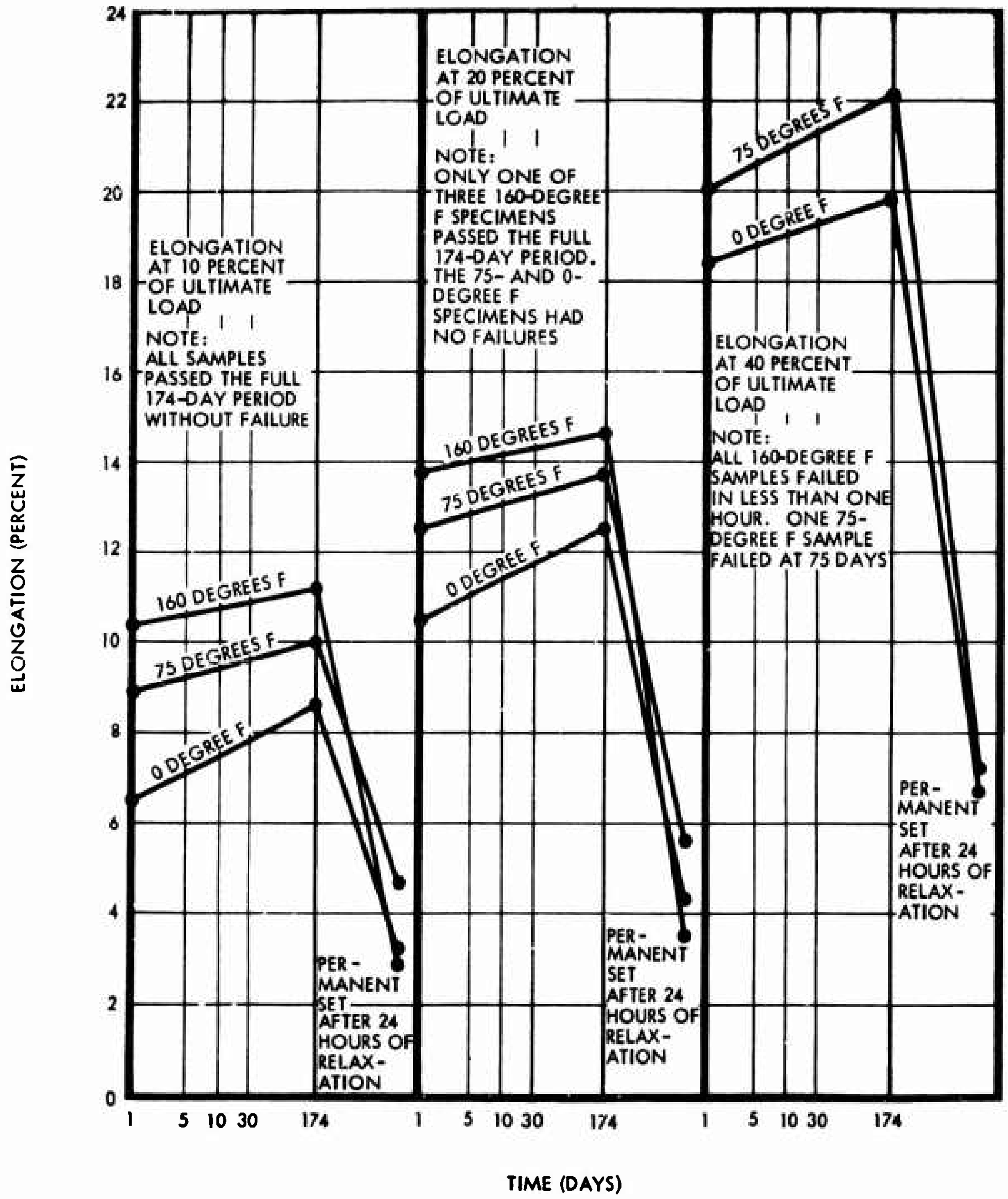

Figure 6. Tensile Creep Test Results.

Tests were performed at approximate sample strain rates of 0.33, 6.6, 17,000, and 30,000 inches per inch per minute. Testing instruments used for these evaluations were described in the section entitled TENSILE TESTS.

Tests were performed at -65, 0, 75, and 160 degrees F at load rates of 0.33, 6.6, 17,000, and 30,000 inches per inch per minute.

As with the tensile tests, prime importance was placed on determination of the effect of varied strain rate and temperature on bond strength. (Results of the tensile lap shear tests are shown in Figures 7 through 9.)

Analysis of Test Results

Analysis of the lap shear test results provides the following conclusions:

1. At slow loading velocities, the polyether elastomers (coded X and Y) have superior lap shear values at the lower temperatures tested but, as the temperature increases, show more progressive degradation than the polyester polyurethane elastomers (coded W and Z) (Figure 7).

2. The W urethane elastomer bond appears to be the strongest at conventional testing speeds. As the strain rate increases, the bond strength remains relatively unchanged until the rate reaches approximately 17,000 inches per inch per minute. The bond strengths of both types of urethane elastomer systems appear to show little change with increasing strain rate until approximately 17,000 inches per inch per minute is reached. A further increase in the sample strain rate produces a significant increase in strength, as can be seen in Figure 8.

3. Both polyether elastomer systems exhibit some rate sensitivity at much lower strain rates than the polyester systems. The magnitude of change of the polyether urethanes is also greater at the higher strain rates than that of the polyester urethanes.

The effect of strain rate at temperatures other than standard is most pronounced in the polyether urethanes (X and Y), as seen in Figure 8. The polyester urethanes (W and Z), although not especially rate sensitive, show less ability to load at high rates than the polyether urethanes. The Y elastomer appears to be the superior material for practically all lap loading conditions.

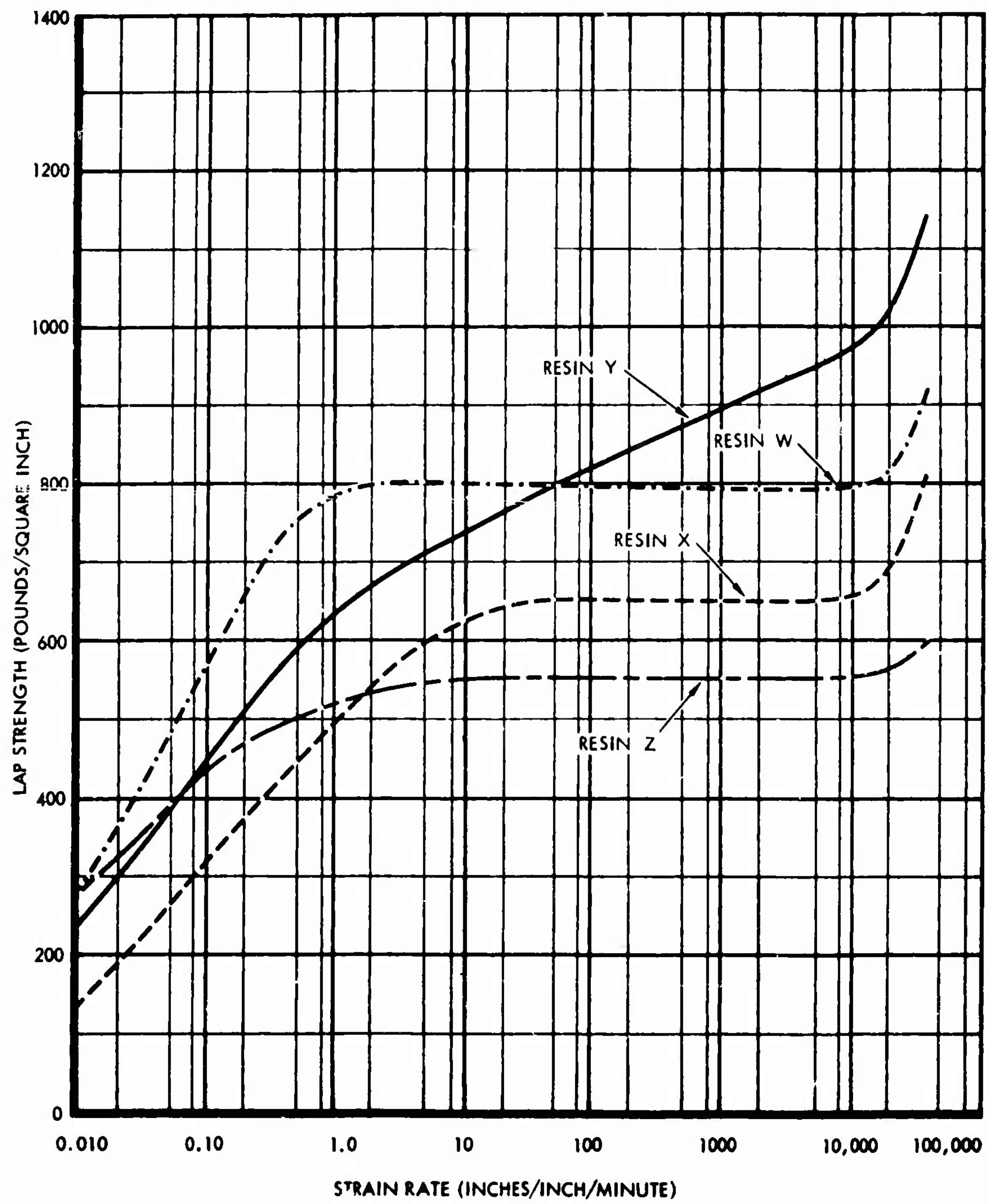

Figure 7. Lap Shear Test (Test Temperature 75 Degrees F).

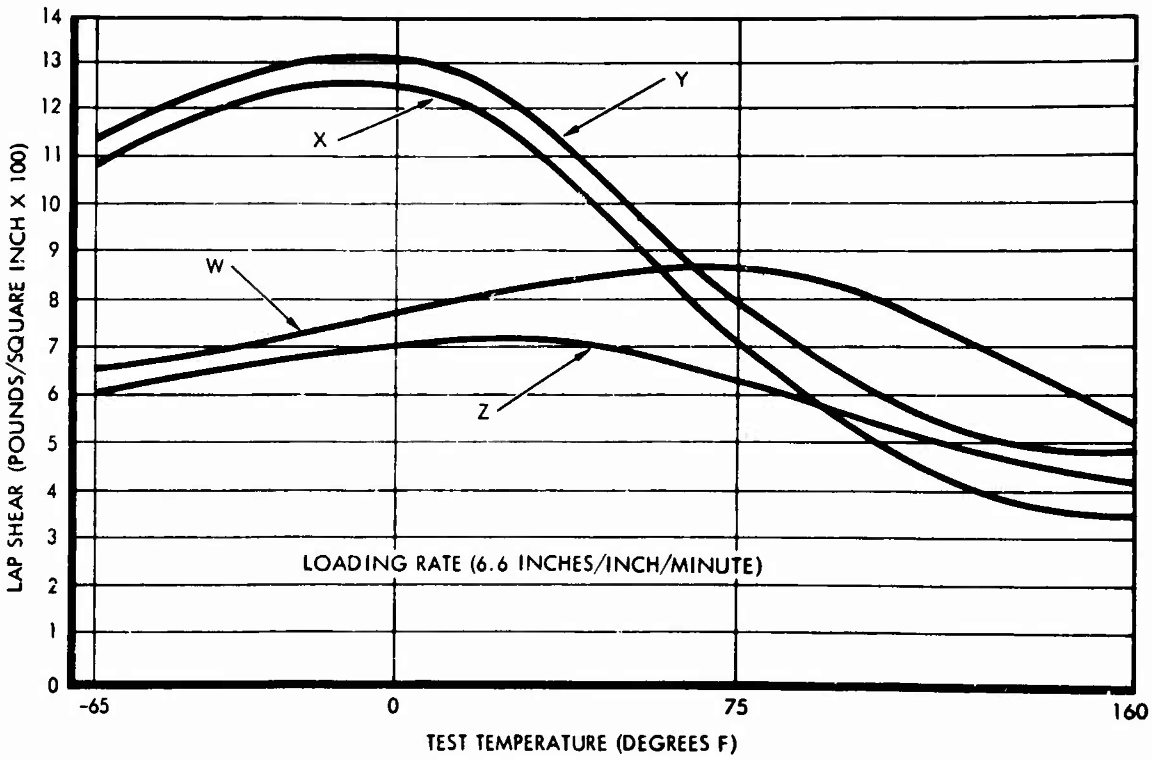

Figure 8. Effect of Temperature on Lap Shear Strength.

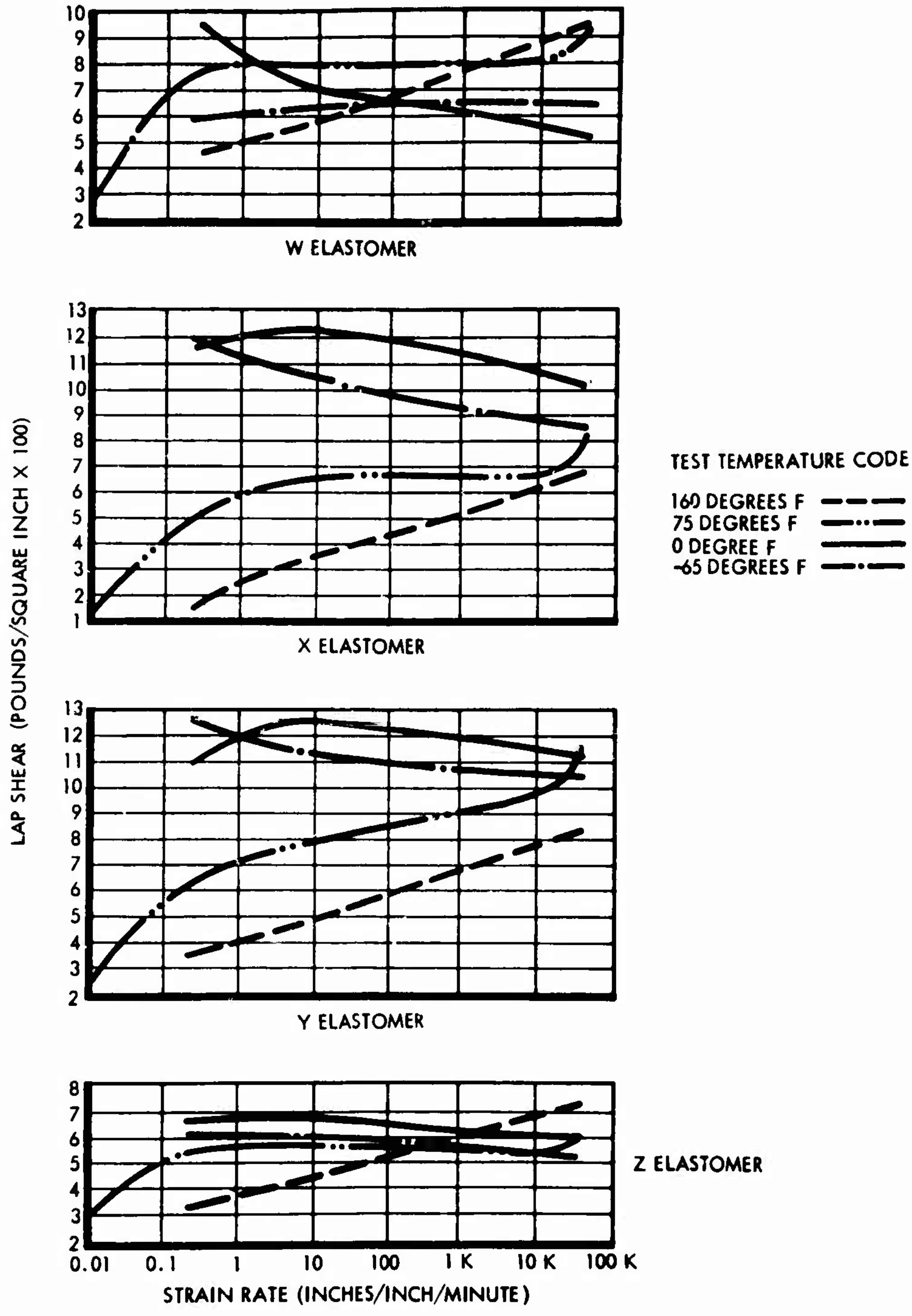

Figure 9. Combined Effect of Strain Rate and Temperature on Bond Strength.

LAP SHEAR CREEP TEST

Lap shear creep tests were performed on all four elastomer systems at temperatures of 0, 75, and 160 degrees F at static loading equal to 10 percent and 20 percent of the average ultimate lap bond strength of each elastomer tested.

Test samples for this series were identical to those used in the standard tensile lap shear tests except that sample width was reduced to 0.25 inch. The supporting structure and individual specimen grips used for these tests were identical to those used for the tensile creep test series. A 6-inch sample gage length was used on all samples.

The weight necessary to produce the desired load levels was carefully applied, and the time-to-lap bond failure (if failure occurred) was recorded.

Test Results

Test results for this series are shown in Table II.

TABLE II
LAP SHEAR STATIC CREEP (SIX-MONTH DURATION)

Elastomer System	Stress Level (Percent Ultimate)	Test Temperatures and Results		
		0°F	75°F	160°F
W	10	No failure	No failure	Failed at 3 hours
	20	No failure	No failure	Failed within 15 minutes
X	10	No failure	Failed at 10 hours	Failed within 16-18 minutes
	20	No failure	Failed within 7-8 minutes	Failed at 1 minute
Y	10	No failure	No failure	Failed at 11 hours
	20	No failure	Failed between 4 and 14 days	Failed within 2 hours
Z	10	No failure	No failure	No failure
	20	No failure	No failure	Failed within 4 hours

Analysis of Results

Both polyester urethane elastomer systems performed better than the polyether urethanes. The marked effect of temperature on these elastomer systems while subjected to static loading can easily be seen. Consequently, it appears that long-term loading of polyester urethane lap joints should not exceed 10 percent of ultimate (based on 20-inch-per-minute values), and the polyether urethanes should be even less. This, of course, poses no serious design problem for fuel cells, since operational strength requirements are but a small fraction of dynamic requirements imposed in a crash environment.

PUNCTURE TEST

Puncture tests were conducted on ARM-018 and ARM-021 materials under various temperature conditions. Specimens were prepared by press-mounting samples over a hollow cylinder of 4.0 inches inside diameter. Samples were locked in place by pressing the retaining ring over the sample and holding cylinder. The sample was thus held taut, and peripheral slippage during impact was negligible (Figure 10). The testing fixture was then placed under the impacting blade and aligned for desired blade-to-ply orientation. The impacting blade (Figure 11), when mounted on the shaft, had a total weight of 5 pounds. This drop assembly was manually hoisted to the test height and released with a sensitive trip device. Two vertical steel cables were used to guide the blade to the test sample accurately.

All tests run at other than 75 degrees F were performed by stabilizing the test sample at the desired test temperature prior to impact.

Test Results

The resultant effect of impact on the test sample was observed, and the degree of penetration was measured. Puncture resistance threshold values were determined by tabulating drop height versus degree of penetration, as shown in Figure 12. The effects of temperature on puncture resistance are shown in Figures 13 and 14.

In addition to the tests conducted on the ARM-018 and ARM-021 composites, specimens of a representative crash-resistant material and .30- and .50-caliber self-sealing materials were also tested. Comparative values are shown in Figure 15.

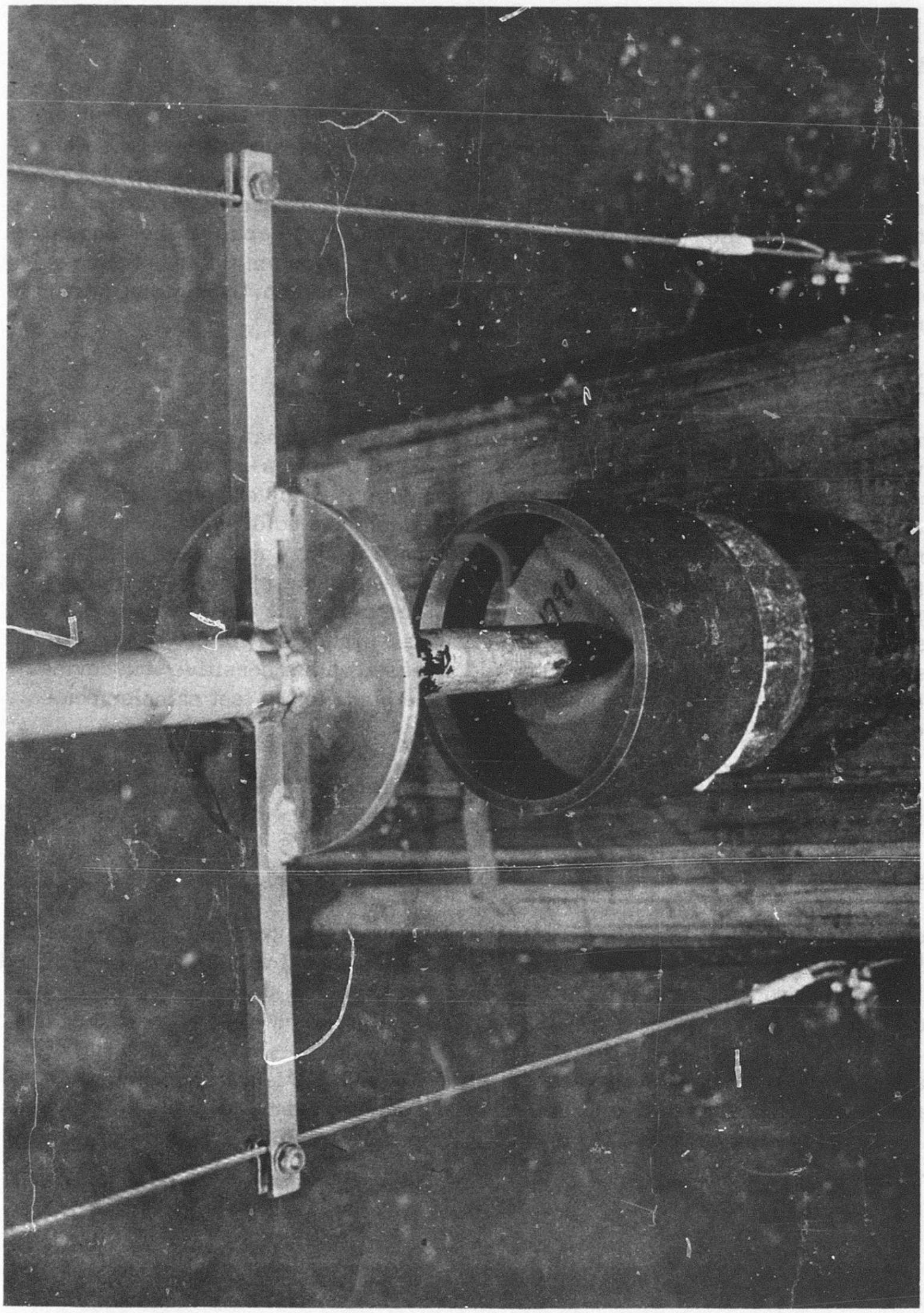

Figure 10. Goodyear Aerospace Puncture Test Detail.

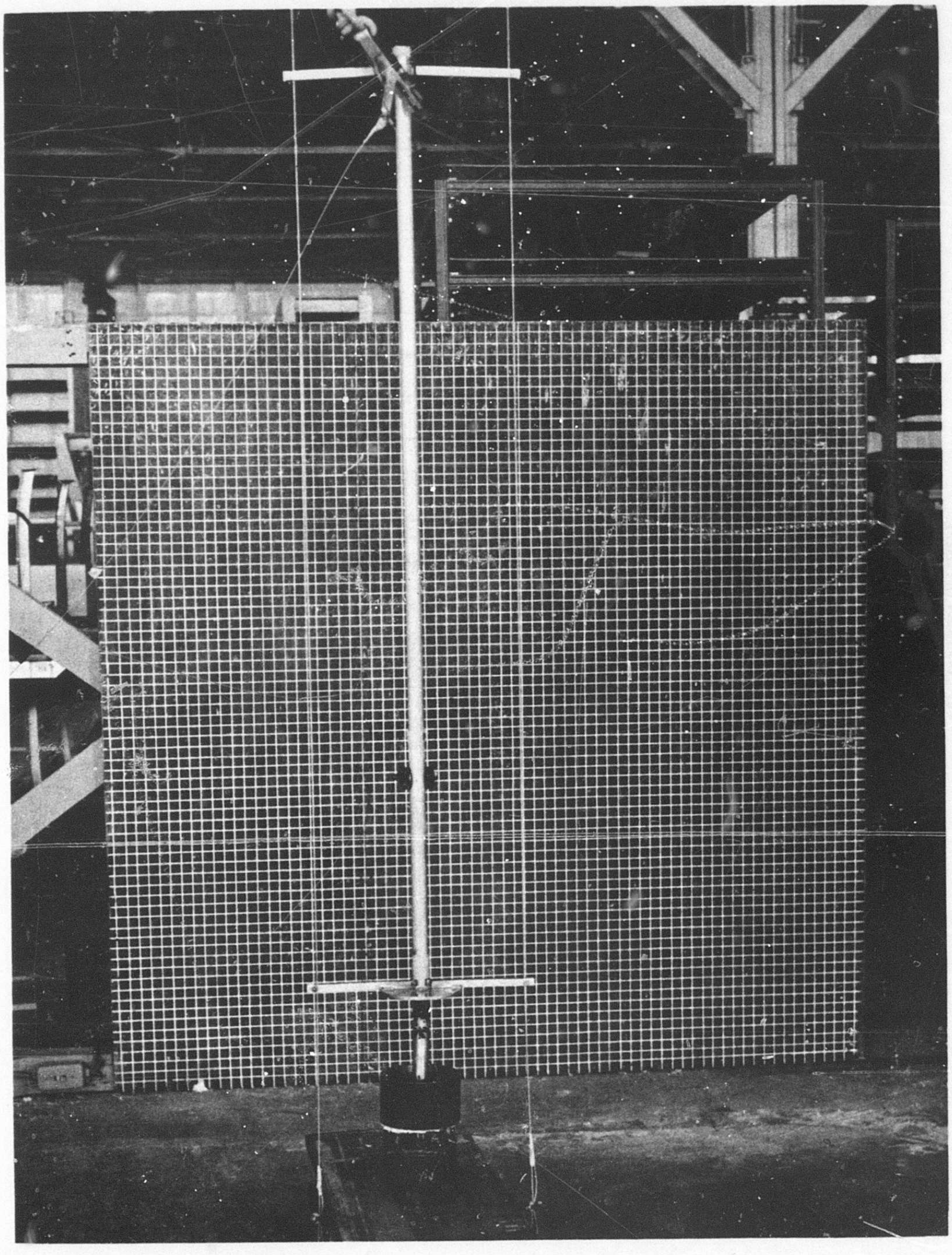

Figure 11. Goodyear Aerospace Puncture Test Apparatus.

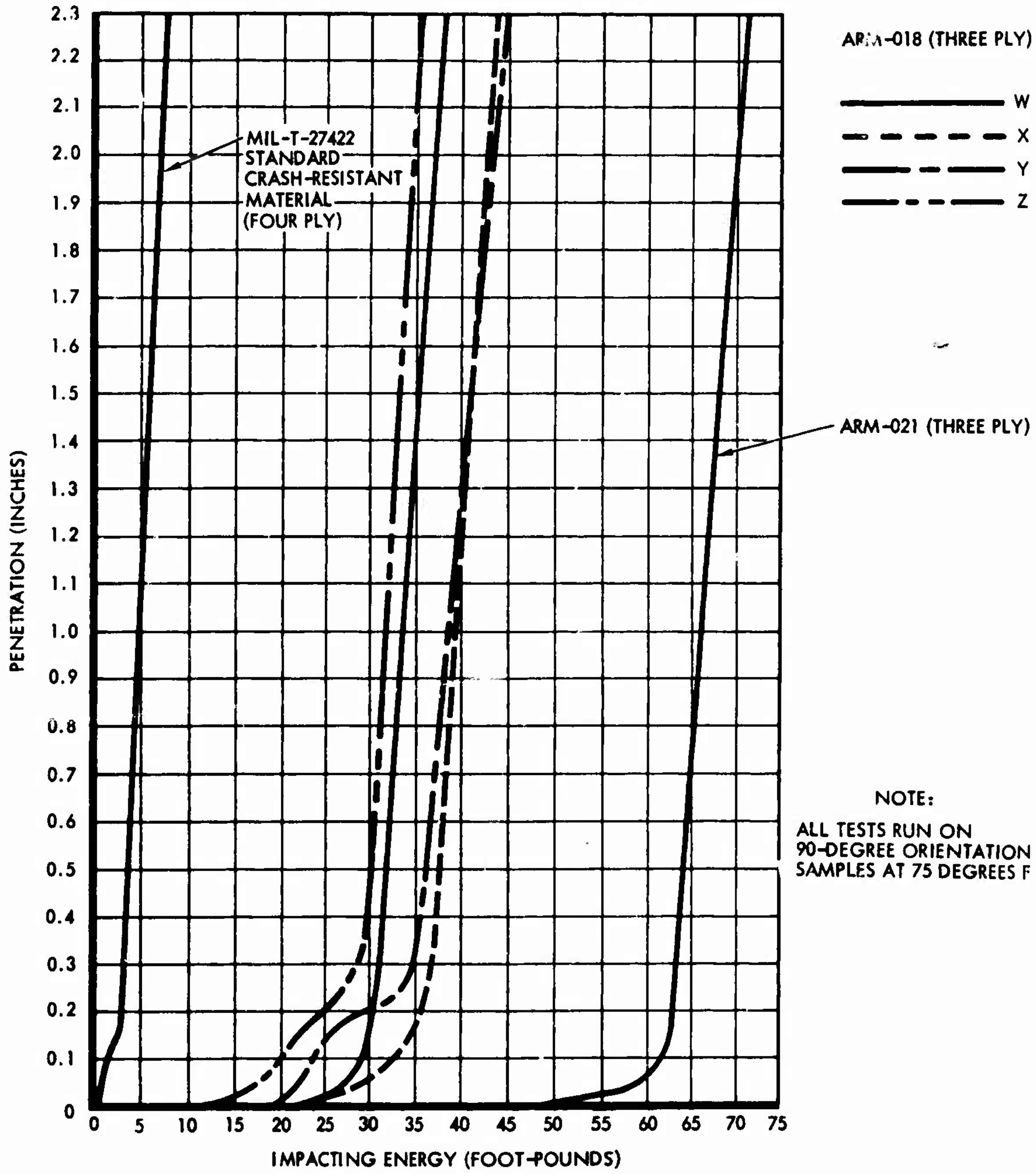

Figure 12. Puncture Resistance (Impacting Energy Versus Puncture Depth).

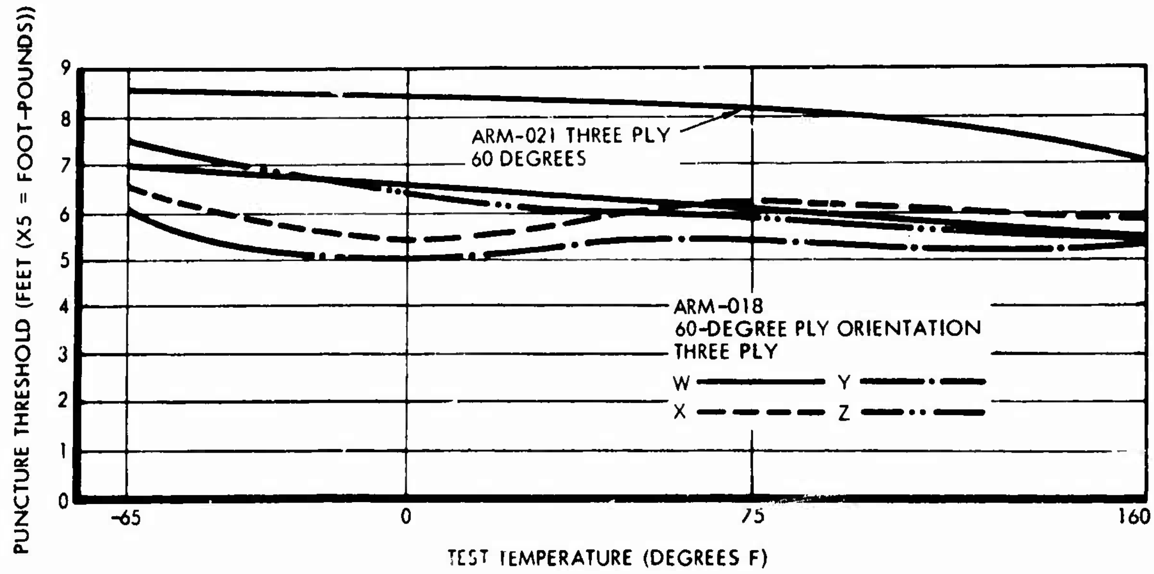

Figure 13. Impact Puncture Resistance at Various Temperatures (ARM-018, ARM-021, 60-Degree Ply Orientation).

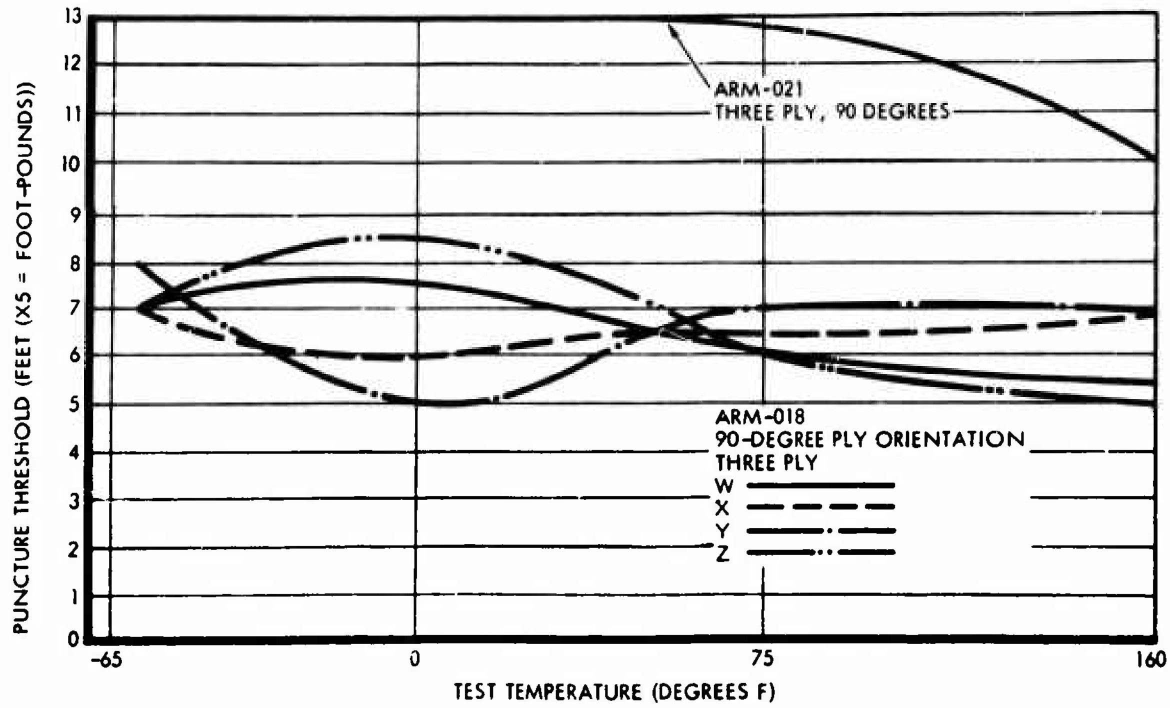

Figure 14. Impact Puncture Resistance at Various Temperatures (ARM-018, ARM-021, 90-Degree Ply Orientation).

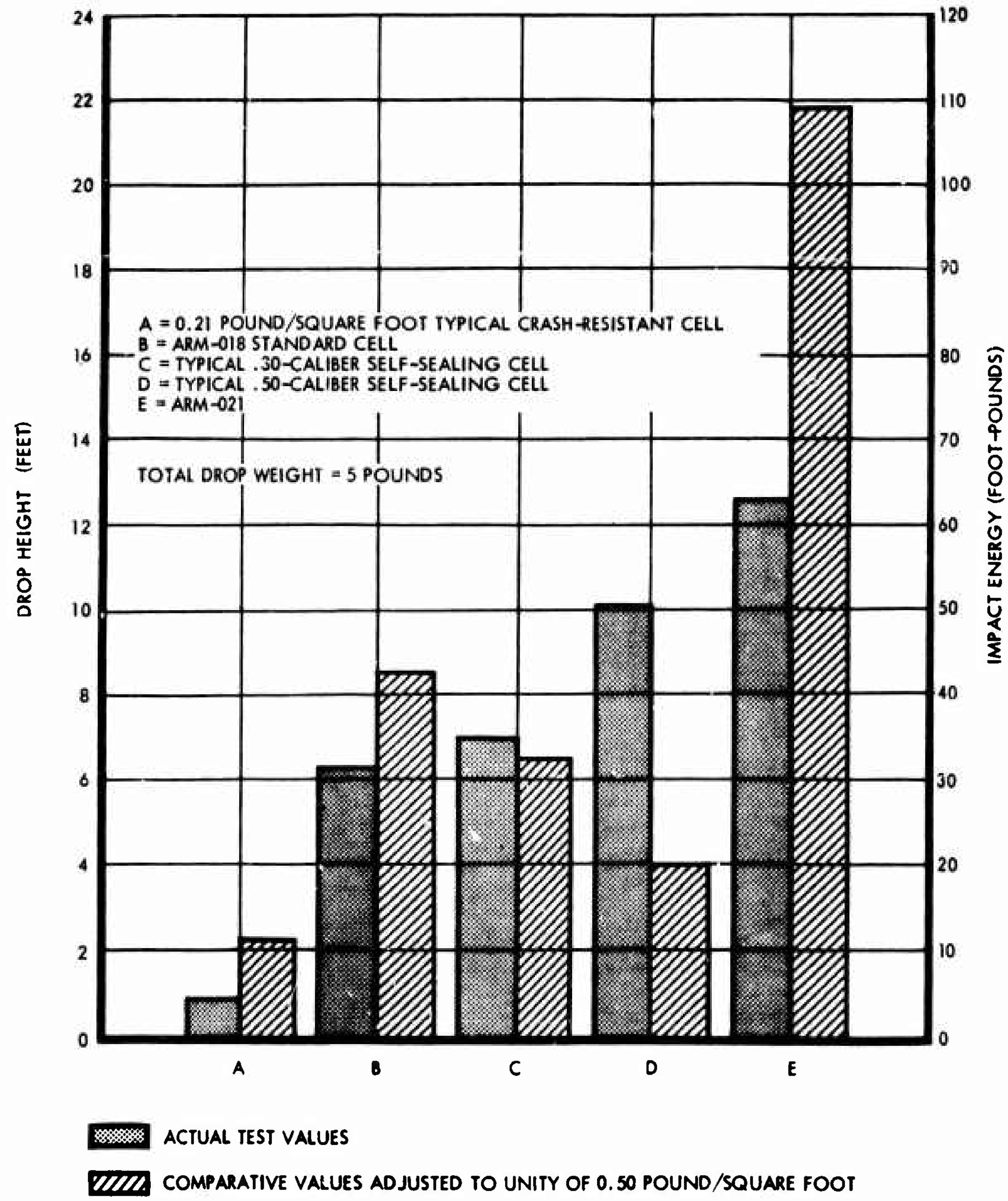

Figure 15. Puncture Resistance.

Analysis of Results

Puncture values of all the ARM-018 composites varied but little, regardless of ply orientation. Temperature also had little effect. Both the ARM-018 specimens and the standard crash-resistant control specimens showed a close correlation of puncture-to-tensile values. The self-sealing tank materials and ARM-021, however, showed puncture values considerably higher than anticipated (Figure 15). This was apparently because the fibers could shift under concentrated loading. The standard self-sealing tanks are constructed of multiaxially oriented plies, these individual plies consisting of unidirectional strands with a weak transverse binding. The ARM-018, while considerably stronger, is of closely restrained, square-woven construction which does not allow fiber displacement. The ARM-021 material contains the same reinforcement as ARM-018. However, the lower strength interlaminar bond of the ARM-021 permits fiber displacement similar to that of the unidirectional reinforcements of the self-sealing cells.

IMPACT TEAR TEST

Impact tear tests were performed on notched samples of ARM-018 and ARM-021 materials clamped vertically in a special holding fixture. This fixture and dimensional details of the samples and impact blade are shown in Figures 16 and 17. Impact tear resistance data were compiled by relating impacting energy to the length of the resultant tear (Figure 18). Except for the blade, the drop apparatus was the same as that described under impact puncture tests.

Tests were run on all four elastomer systems of the ARM-018 construction and on the ARM-021 material using three-ply laminates with both 60- and 90-degree ply orientation. Both low (20 to 23 percent) and standard (35 to 40 percent) elastomer content samples of the ARM-018 construction were tested at temperatures of -65, 0, 75, and 160 degrees F. These tests were made from a height of 20 feet with the impact apparatus weighted to 5 pounds.

All tests run at other than 75 degrees F were performed by stabilizing the test sample mounted in the test fixture at the desired test temperature prior to impacting.

To determine the effect of loading rate on resultant tear, the standard elastomer content tests were rerun from a height of 2 feet with the drop apparatus weight adjusted to 50 pounds, thus yielding a comparable impacting energy at a much reduced velocity.

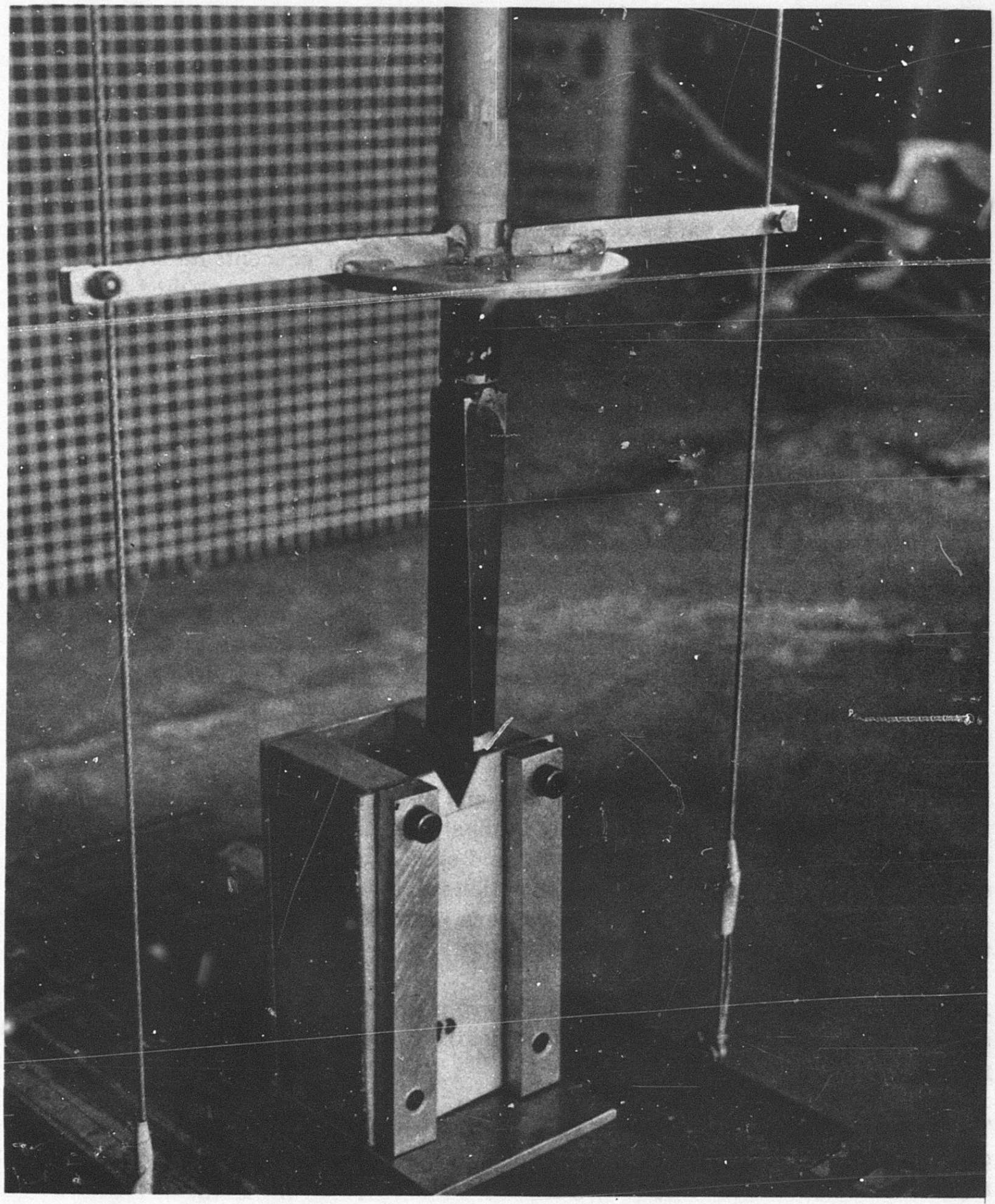

Figure 16. Edgewise Tear Test Apparatus and Mounted Specimen.

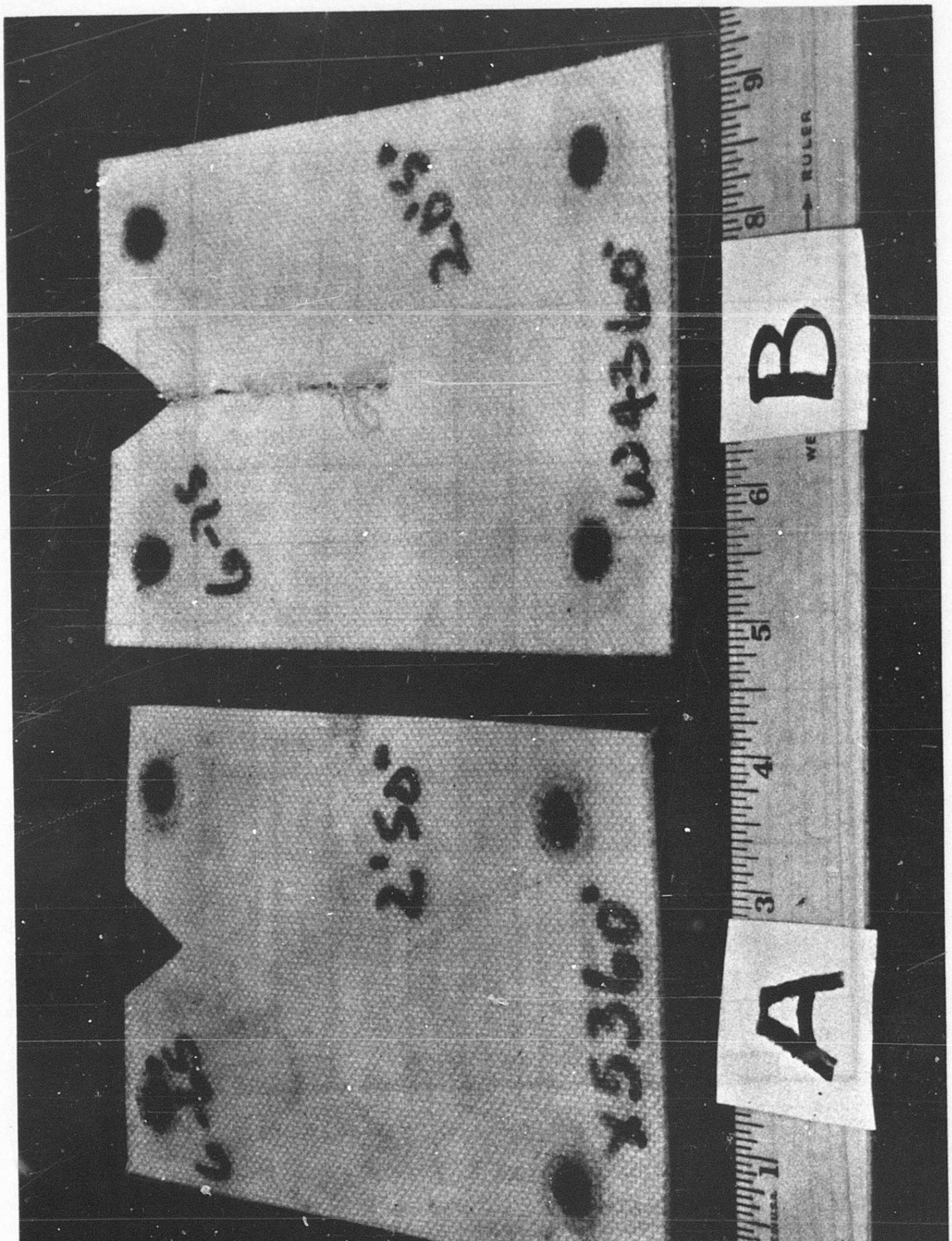

Figure 17. Impact Tear Test Samples.

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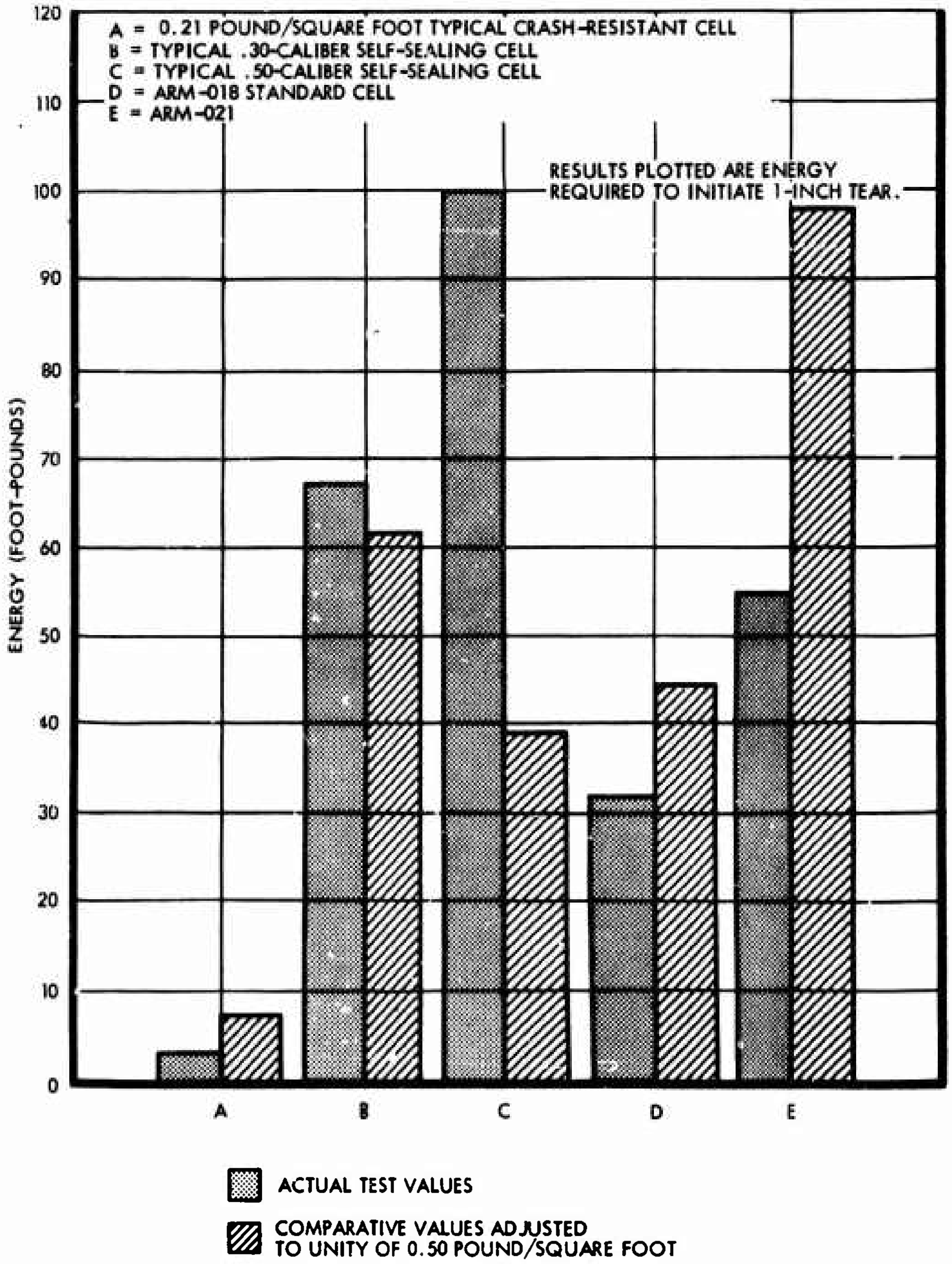


Figure 18. Impact Tear Test.

Control specimens of a crash-resistant tank material, qualified to MIL-T-27422, and .30- and .50-caliber self-sealing materials, qualified to MIL-T-5578, were tested for comparative values.

Test Results

Results of the impact tear tests are shown in Figures 18 and 19.

Analysis of Test Results

The room-temperature tear depths of the several ARM-018 laminates varied from 2.6 to 5.5 inches. At above 0 degree F temperatures, the tear resistance appeared dependent on the stiffness of the urethane elastomer. The softer the elastomer, the better the values. At below 0 degree F temperatures, there was an inversion of these values. Apparently, this was caused by increase in strength of the X and Y polymers and by the brittleness of the W and Z polymers. This brittleness induced delamination prior to failure of the fibers, thus permitting the fibers to shift to a limited degree.

Tear values of the 60-degree oriented laminates generally showed little, if any, advantage over the 90-degree orientation.

Impacts at elevated temperatures showed the best values, apparently because of the softening of the elastomer, once again permitting the reinforcement fibers to shift and group against progressive failure.

The .30- and .50-caliber self-sealing materials showed a high resistance to tear, but the standard crash-resistant material was very poor. The reason, again, was apparently because the fibers of both self-sealing materials could shift under local impact while those of the standard crash-resistant material could not.

CONSTANT RATE TEAR TEST

Constant rate tear tests were performed on all four elastomer systems of the ARM-018 material and the ARM-021 with both 60- and 90-degree three-ply orientation. Tests were conducted on standard elastomer content samples of ARM-018 (35 to 40 percent) and the ARM-021 at -65, 0, 75, and 160 degrees F. Further tests were made at 75 degrees F on all four systems and both ply orientations of the ARM-018 having low elastomer contents (20 to 23 percent).

A sample configuration 8 inches long by 3 inches wide was adopted for this test series. Samples were prepared for testing by making a 3.0-inch-long cut through

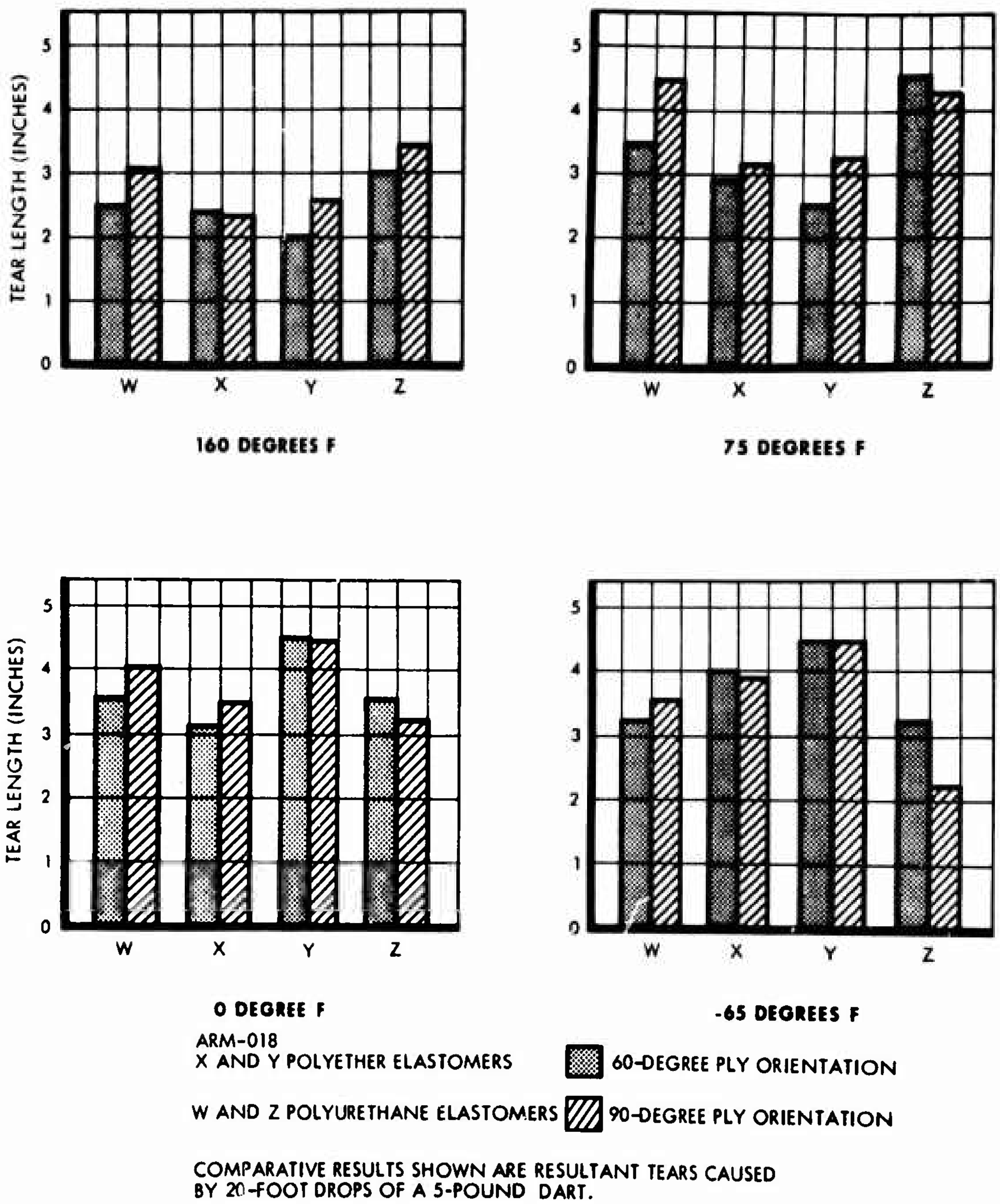


Figure 19. Impact Tear Tests at Various Temperatures.

the center of the test specimen parallel to the long dimension (sample A in Figure 20).

The samples were pulled at a constant 20-inches-per-minute rate, thus propagating the initial tear (Figure 21). Autographic record of the entire test was made, and the tear resistance was calculated by averaging the five initial peak loads recorded.

Test Results

The constant rate tear test results are shown in Figure 22 and Table III.

TABLE III
CONSTANT RATE TEAR TEST (75 DEGREES F)
LOW ELASTOMER CONTENT (20 TO 23 PERCENT)

ARM-018 Elastomer Type	60-Degree Ply Orientation (Pounds)	90-Degree Ply Orientation (Pounds)
W	352	487
X	777	575
Y	1132	1175
Z	379	398

Analysis of Test Results

The standard elastomer content tests of the ARM-018 indicate that in all instances the 60-degree reinforcement ply orientation offered greater tear resistance. This was as expected and is caused by the bias ply acting to restrict the progression of linear tearing. All 90-degree ply samples tested failed in a linear tearing mode (Figure 20(B)), while the 60-degree ply orientation failed through a combination of tearing and ply peeling (Figure 20(C)).

The low elastomer content test results show that the benefit of tear resistance achieved with the 60-degree ply orientation is reliant on interlaminar bond

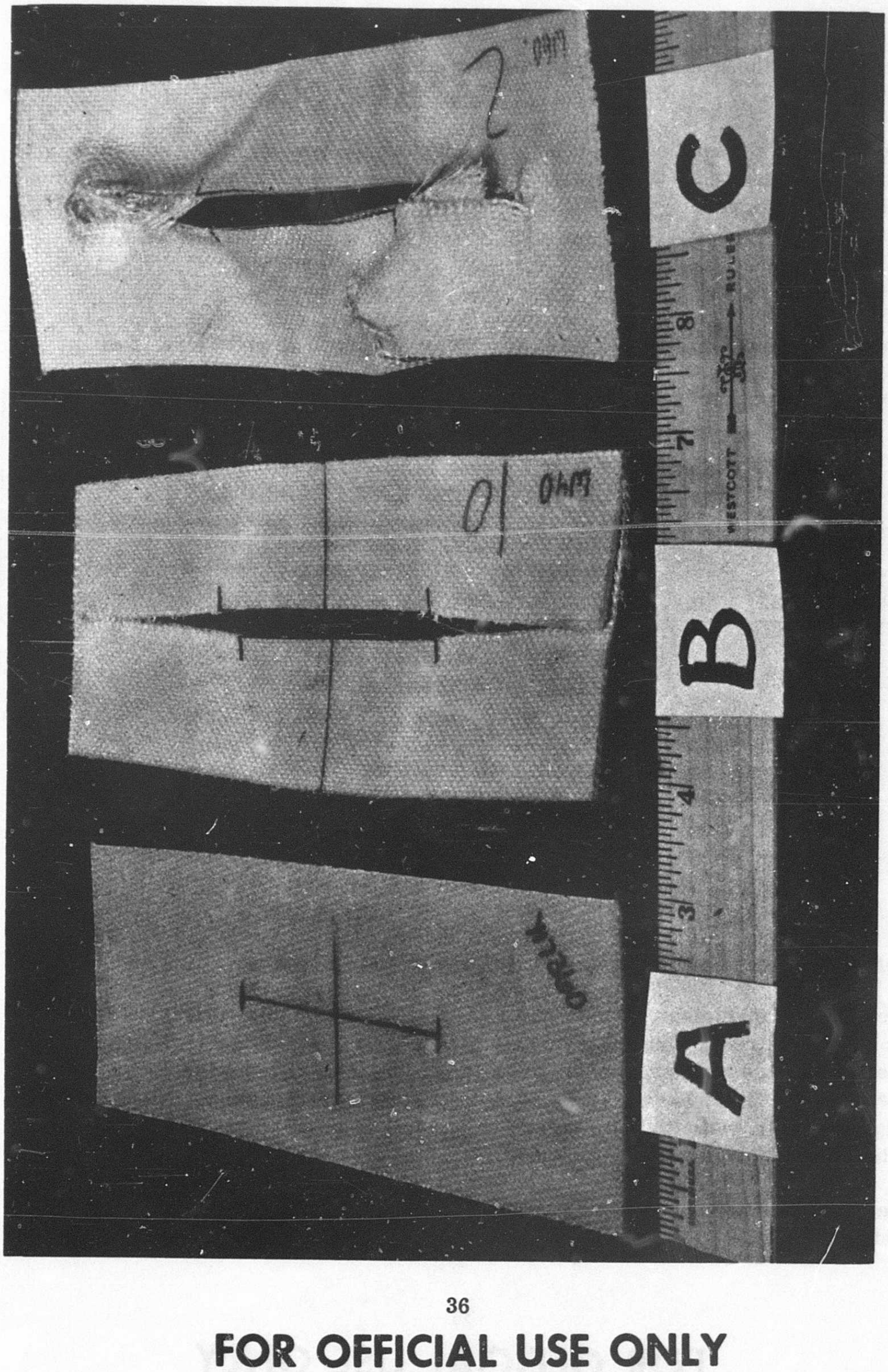


Figure 20. Constant Rate Tear Samples.

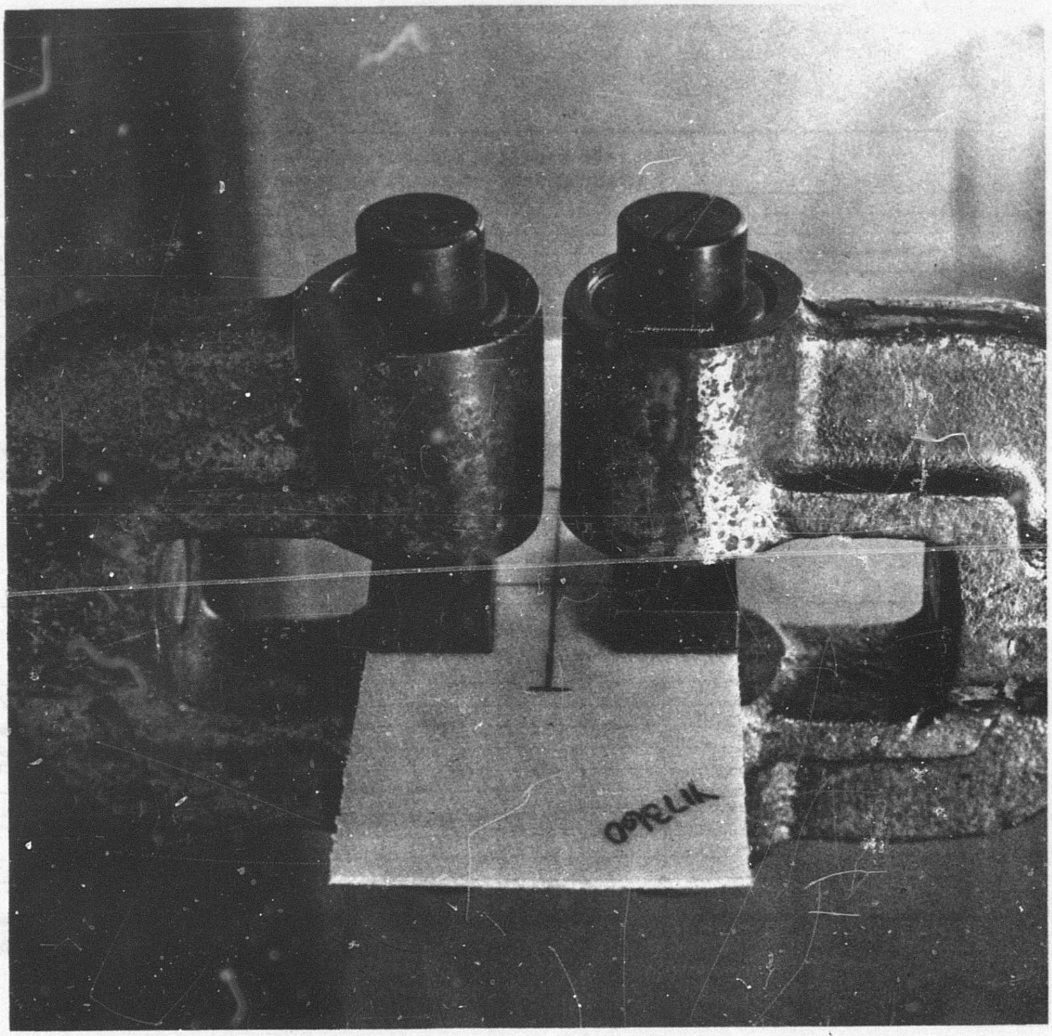
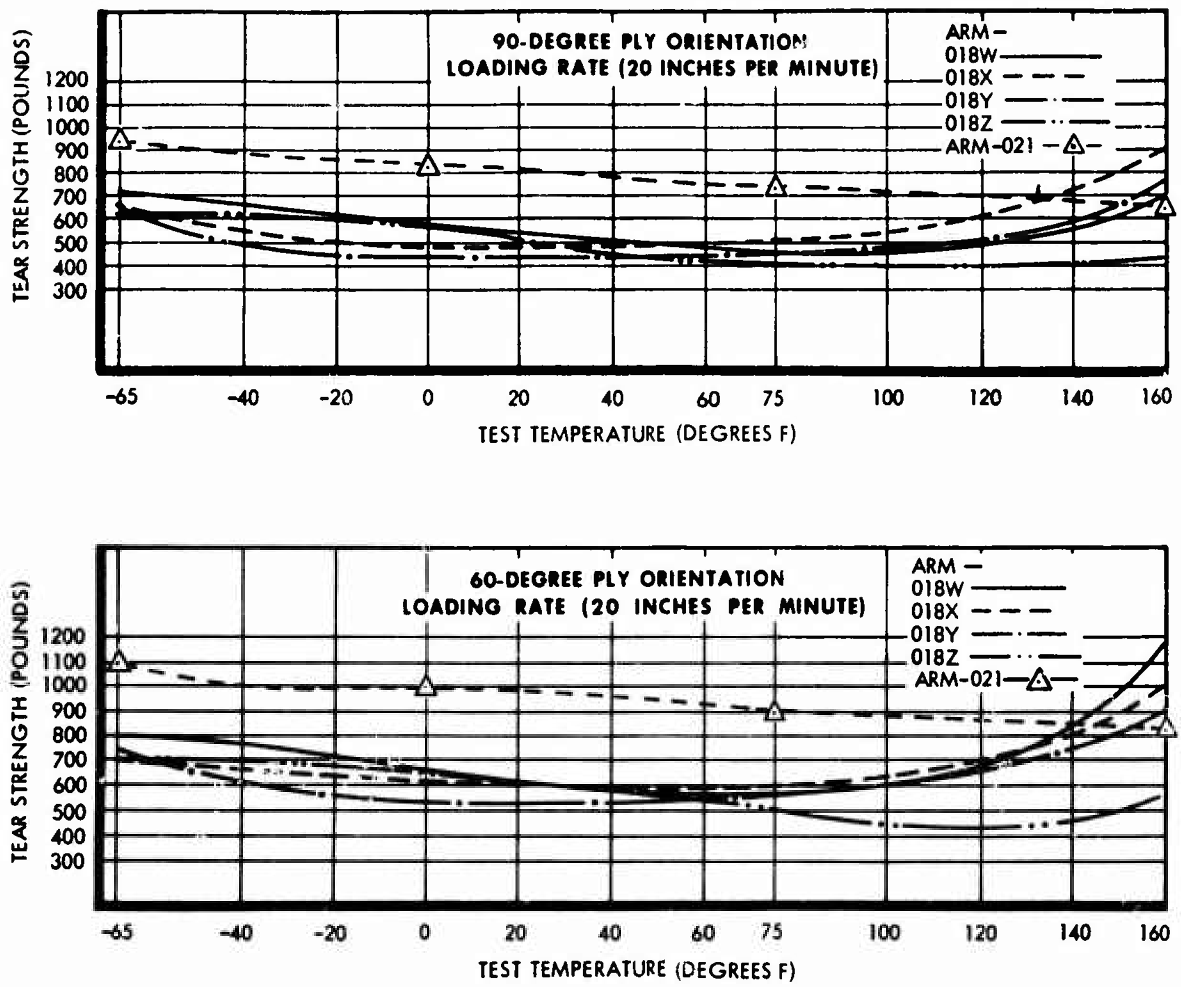


Figure 21. Constant Rate Tear Test.



NOTE: ALL SAMPLES CONTAIN STANDARD ELASTOMER CONTENT
ARM-018-35 TO 40 PERCENT
ARM-021-10 TO 15 PERCENT

Figure 22. Constant Rate Tear Values.

strength in the ARM-018 construction. As the elastomer content decreases, the interlaminar bond strength is reduced and no longer offers as much benefit through peel resistance.

The ARM-021 construction, because of its different processing, results in an essentially dry fiber reinforcement. The binding elastomer is restricted to the outer fiber surface while the ARM-018 elastomer partially saturates the reinforcement fiber. The higher tear strength of the ARM-021 results from this processing modification which allows better fiber grouping to occur. As was found with the ARM-018, the 60-degree ply orientation of the ARM-021 is stronger than the 90-degree orientation.

This test specimen configuration is believed to simulate very closely the conditions encountered by a tank in crash environments, where combined puncture and hydraulic surges often cause catastrophic tearing. However, the test lacks the ability to simulate dynamic loading rates, and, therefore, the results are of questionable value. This same test, conducted under impact conditions, would probably yield more realistic crash simulating results.

BEARING TESTS

Bearing tests were performed on ARM-018 W laminates of 37-percent elastomer content. This test series was run to simulate bearing stresses induced by bolts in filler neck assemblies and other fittings. Tests included several laminate thicknesses, bearing pin diameters and sample widths. The effect on bearing strength of punching versus drilling the holes was also evaluated. The bearing test apparatus generally conformed to that shown in method 1051 of Federal Test Method Standard 406 with the variations as noted. A bearing pin pullout rate of 20 inches per minute was used for all tests. Bearing tests were not performed on the ARM-021 because of this material's low resistance to local deformation. Areas of ARM-021 construction requiring mechanical attachments are more highly impregnated with elastomer to ARM-018 construction level.

Test Results

Bearing test results are shown in Table IV. Values are based on an average of five tests of each type.

Analysis of Test Results

The test results indicate a straight-line correlation of values of various thicknesses. The 90-degree orientation showed a slight advantage over the 60-degree orientation. Surprisingly, the 1/8-inch-diameter pins showed better values than

TABLE IV

BEARING TEST

Number Ply	Ply Orientation (degrees)	Pin Diameter (inches)	Edge Distance (inches)	Sample Width (inches)	Hole Preparation	Ultimate Load (Pounds) (Average)
3	90	1/8	3/4	0.94	Drilled	454
3	60	1/8	3/4	0.94	Drilled	457
3	90	1/4	3/8	0.94	Drilled	434
3	60	1/4	3/8	0.94	Drilled	394
6	60	1/4	3/8	2.0	Punched	800
6	90	1/4	3/8	2.0	Punched	866

the 1/4-inch-diameter pins, with equal values for th[illegible] legree and 60-degree orientations.

IMPACT DROP TESTS

Several attempts were made at devising a qualitative impact test for fuel tanks. The first of this series consisted of testing cylindrical tanks for flat impact and for resistance to puncture from irregular protrusions. These tanks were of three-ply, 60-degree orientation ARM-018 W construction.

Tanks containing various weights of water were dropped from measured heights. Drops were made both flatwise and onto anvils of several configurations.

Tank attitude during the drop was controlled by tabs bonded to the tank top and bottom. These tabs engaged two vertical guide cables to ensure proper attitude of impact. Drop tanks and test site are shown in Figures 23 and 24.

Flat Impacts

The first test series consisted of flat impacts on tanks filled to capacity with water (80 pounds). The first tanks were fitted with a pressure transducer to measure pressure surges upon impact, but the impact accelerations were so great that the transducer was severely damaged, and pressure data had to be calculated by measuring diametric deflection as recorded by high-speed motion pictures. This deflection was then correlated with the strain data gathered in the high-speed tensile test series, and hoop stresses were calculated accordingly. Results are shown in Figure 25.

Anvil Impacts

Anvil impacts were made on various shapes. The first type to be tested was a duplication of the 90-degree blade used by AvSER. Because of the highly directional aspects of this device, other anvils were tested to limit directional aberrations in the values. The results of these tests are shown in Figure 26.

DISCUSSION OF TEST RESULTS AND ANALYSIS

Flat Impacts

The flat impacts from 40 feet did not attain the energy necessary to rupture any of the tanks, except for one individual tank which had been built to test the strength of secondary bond lap seams. In this test, the longitudinal 3-inch lap seam failed on the second drop from a height of 40 feet (Figure 27).

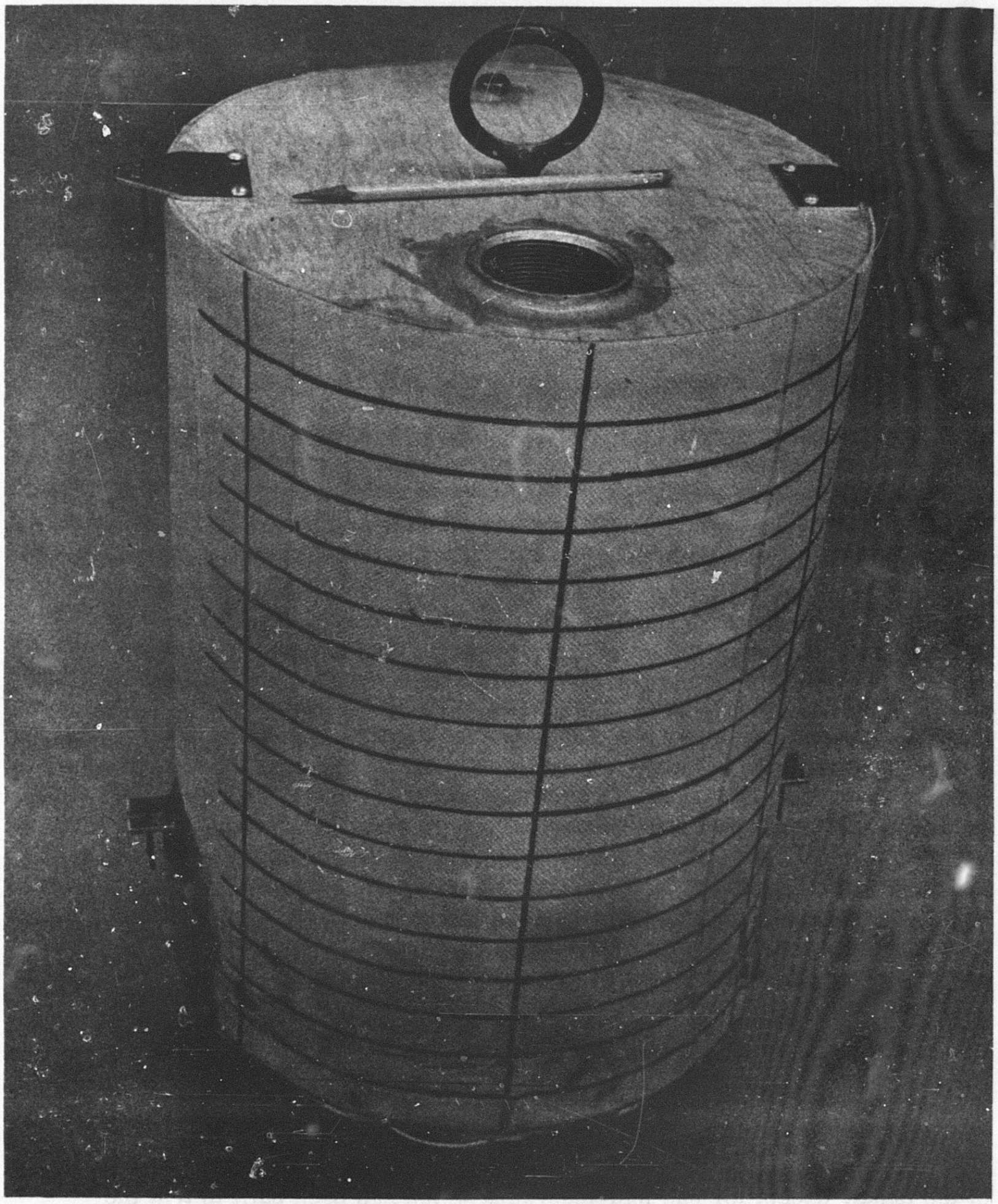


Figure 23. Cylindrical Tank.

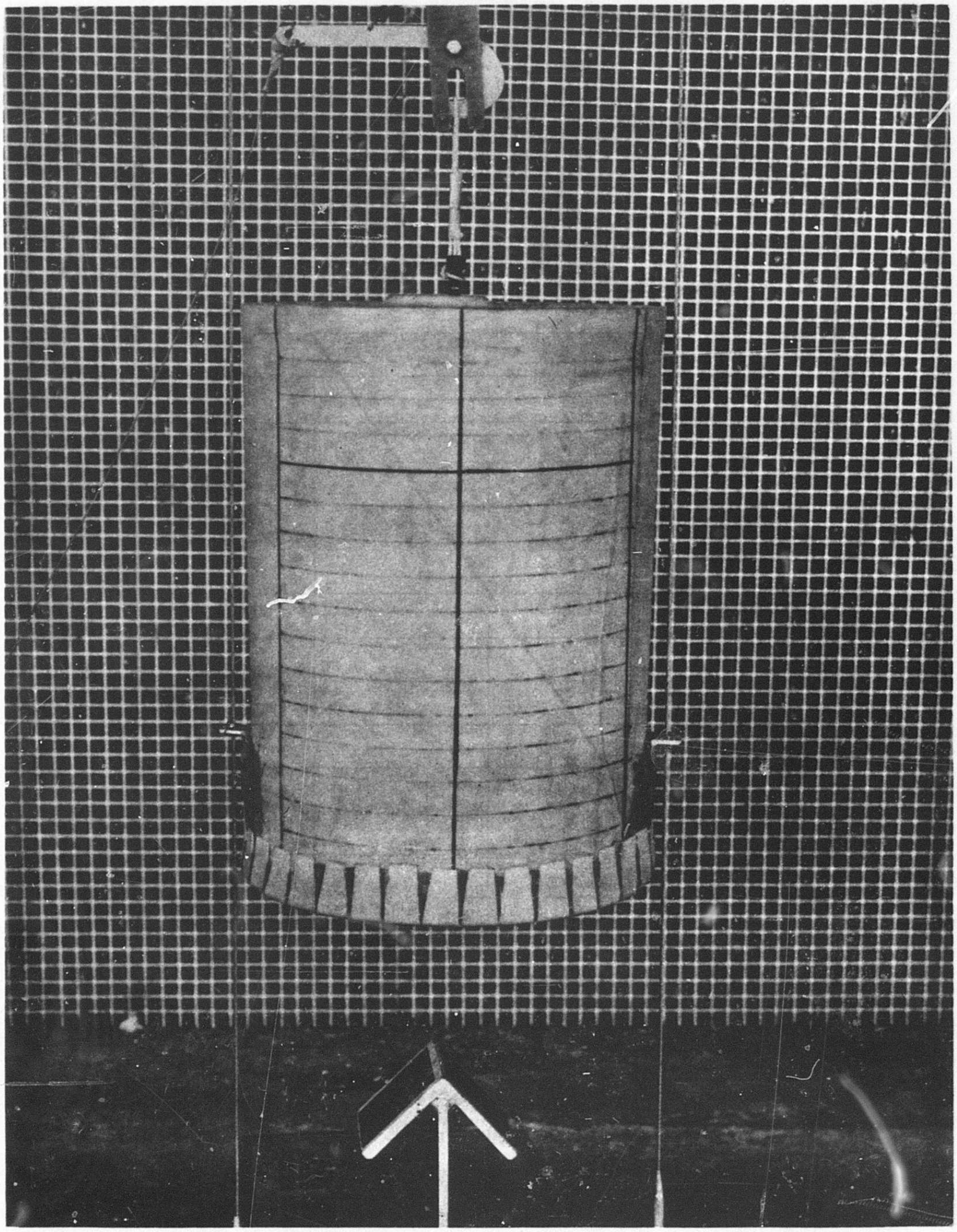


Figure 24. Tank Drop Test Site.

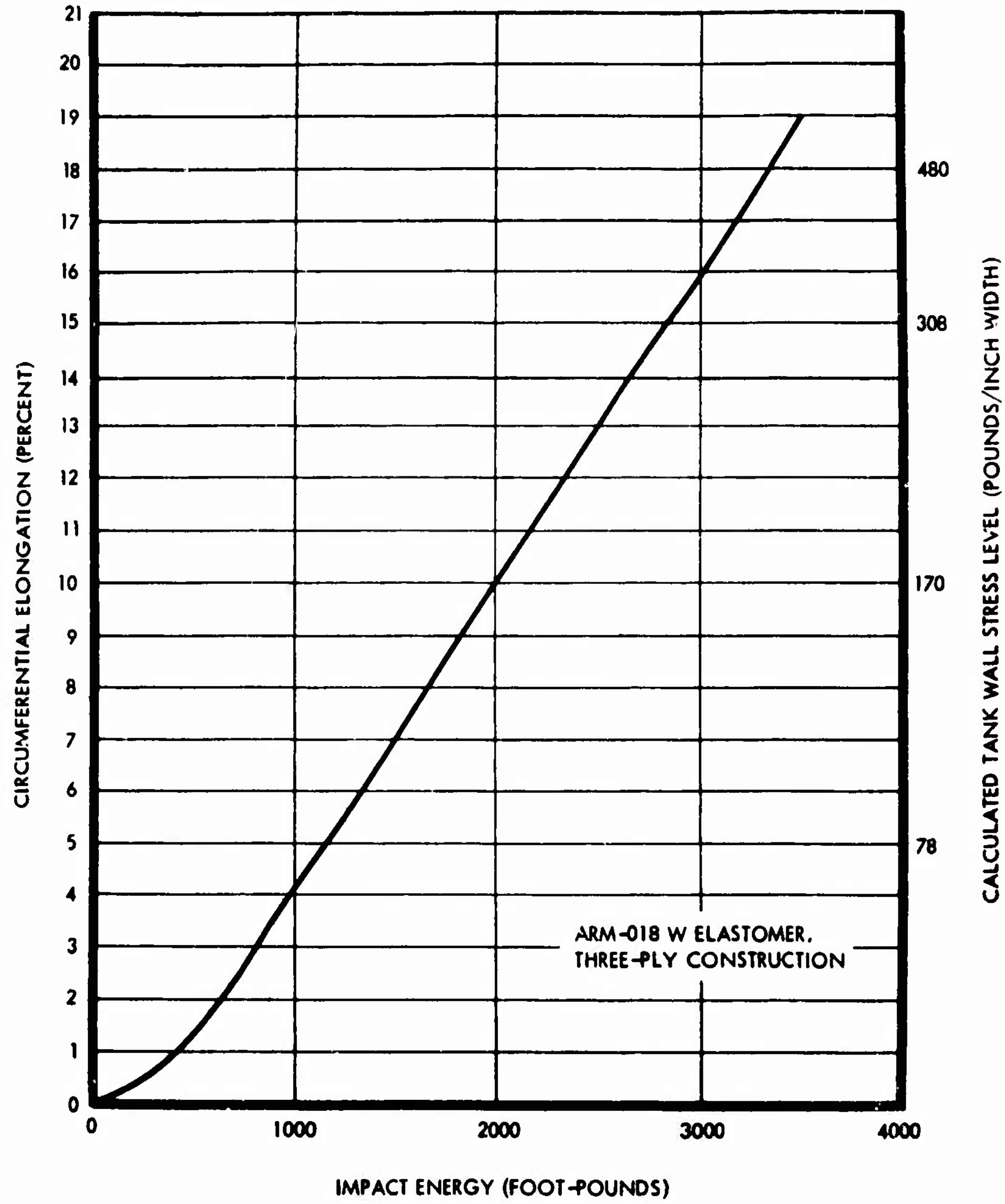


Figure 25. Cylindrical Tank Flatwise Impact Drop Test.

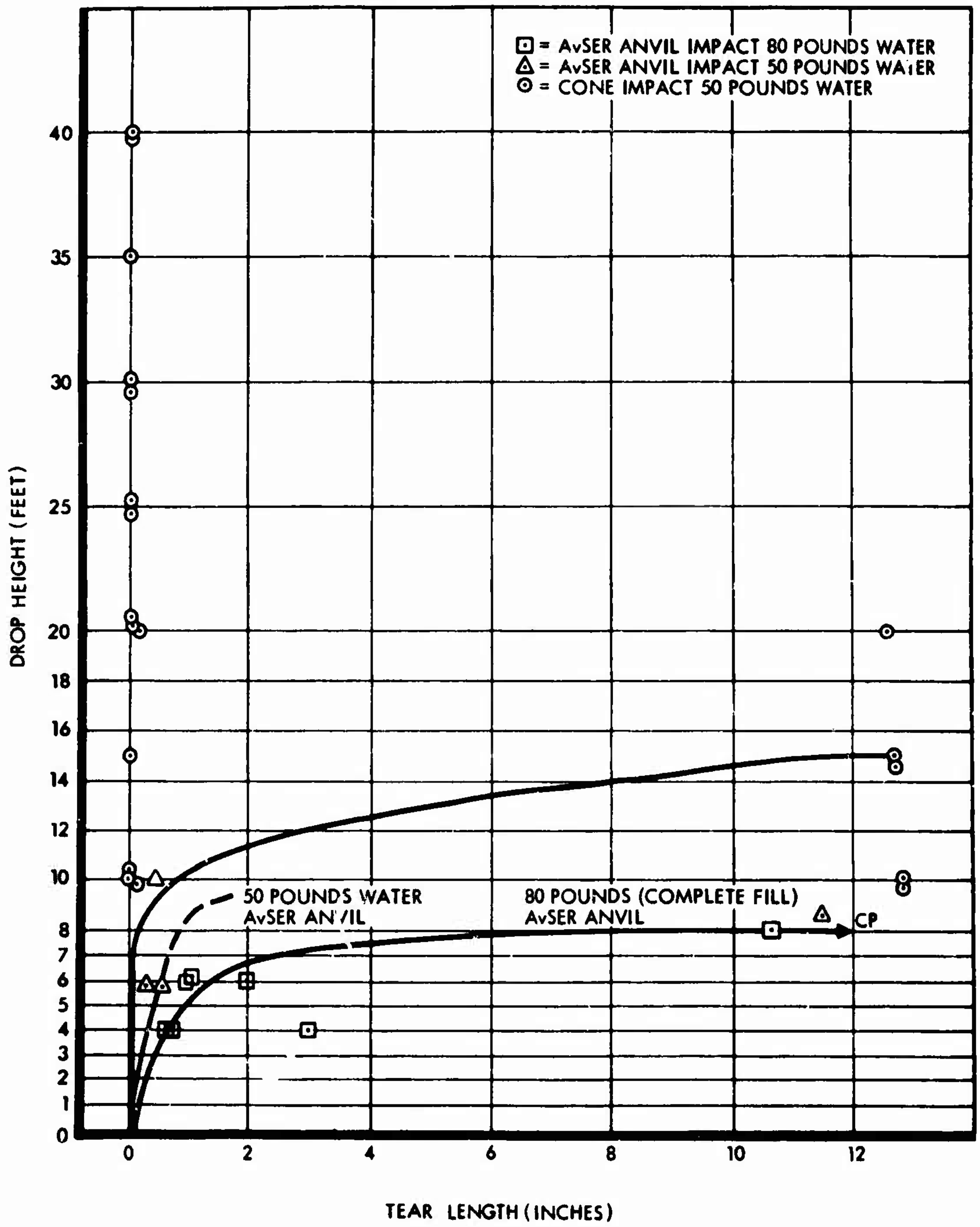


Figure 26. Cylindrical Tank Anvil Drop Test.

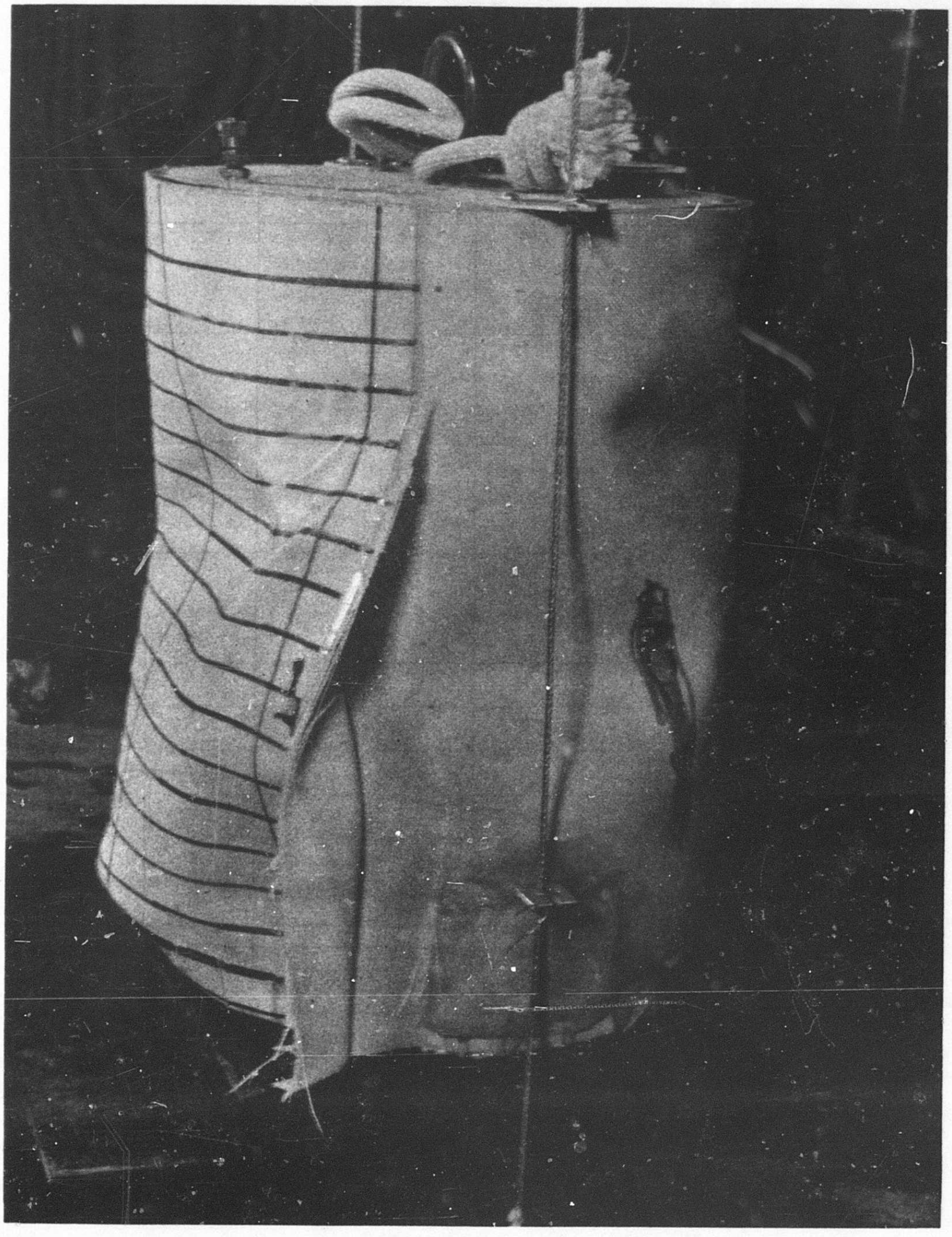


Figure 27. Cylindrical Tank Seam Failure.

The tanks experienced circumferential elongation near the base averaging 17-18 percent when dropped from 40 feet. Based on tensile load deflection data, this indicates that the tanks were within 20 percent of their ultimate load. A permanent set of about one-half percent occurred after several consecutive impacts from 40 feet, indicating that the yield point of the ARM-018 is very close to its ultimate stress.

The first tanks tested in this series had no internal liner membranes. Initial leak tests showed no fluid loss. Yet, after even moderate impacts (20 feet), some signs of wicking began to appear, indicating failure of the elastomer bond under strain conditions of less than 11 percent. Apparently this did not cause any reduction of physical strength to the tanks.

The flat impact tests were of some limited value in indicating the degree of permanent set under impact and in substantiating the permeability data concerning the breaking down of the elastomer bond under high strain conditions. However, there was little to recommend it as a qualitative test, and this portion of the series was terminated.

Anvil Impact

The AvSER-type anvil, initially used in this series, showed considerable scatter of data when used to test the cylindrical tanks. This was probably caused more by the tank geometry than by the anvil. The greatest disadvantage of this anvil was that the multiplicity and irregularity of tearing precluded the establishment of satisfactory ratings reflecting the magnitude of tank damage.

Experiments with the conical anvil proved to be even more erratic than the AvSER anvil when testing cylindrical tanks. Because of the nondirectional properties of the cone, just the reverse effect would be expected. The answer was found when a study of the base perimeters of the tanks showed considerable differences in their ability to buckle under loading. If a tank could be "broken in" by repeated buckling of the perimeter using low-level impacts, then even the most severe impacts would not cause failure. If, on the other hand, a tank had a uniformly stiff base perimeter, then puncture values would probably be quite low.

With this, it was evident that the cylindrical tanks would not be satisfactory for qualitative cell tests, and this portion of the study was closed.

Cube Tank Tests

Because of the inability to gather qualitative test data from cylindrical tanks, the effort was directed to work with cube tanks. Since cube tanks are standard for

Phase I cell qualification under MIL-T-6396 and MIL-T-5578, it was felt that similar size tanks would offer an excellent means of gathering comparative impact data. The size and shape also appeared to be ideal for simulating aircraft cells.

Initial tests for feasibility of cube tanks were made on 12-inch cube ARM-018 W tanks. These tanks were filled to capacity with water and dropped from heights ranging up to 40 feet on both flat surfaces and on the 90-degree conical anvil. Several 40-foot drops were made, both flatwise and on cone anvils, with no failure occurring.

The tanks of this series were obviously too small for truly meaningful results. However, studies of tank distortion in this series fortified the opinion that the 30-by-30-by-24-inch cubes would perform the test function satisfactorily.

Large Tank Tests

The first two large-size cells, 30-by-30-by-24 inches, were made of ARM-018 W laminates. Both of these cells were constructed with 3-inch secondary lap joints in the hope of gathering substantiating data to determine whether this type of joint could be used in fuel cells. The tanks were dropped flat onto a concrete slab from a height of 20 feet.

Experimental Results

Both tanks suffered catastrophic rupture of the lap seams. Consideration was given to increasing the lap area width. Failure of these lap seams was in the reinforcement ply adjacent to the elastomer bond. It became increasingly apparent that the secondary lap joint was not a satisfactory load transfer medium. A technique of cell fabrication using staggered ply laps was then adopted, with excellent results. However, because of the relatively low resistance of the ARM-018 cells to puncture and tear, all further testing of this type was done on the ARM-021 material. A four-ply tank was fabricated using the ARM-021 construction with staggered ply laps. This tank was filled completely and contained 770 pounds of water. It was dropped flatwise from a 20-foot height without sustaining damage.

The use of increased drop heights for qualitative evaluation was undesirable, so consideration was given to dropping the tanks on an anvil. The four-ply ARM-021 tank which had withstood the 20-foot flat impact was again tested using an anvil. The tank, still filled with 770 pounds of water, was dropped from 20 feet onto an 8-inch-diameter, 90-degree cone with a 1/2-inch nose radius (Figures 28 and 29). Total height of the anvil was 10 inches. The tank did not fail; however, examination of high-speed movie coverage taken during the test confirmed that

Figure 28. Drop Test Anvil (90 Degrees, 10 Inches High).

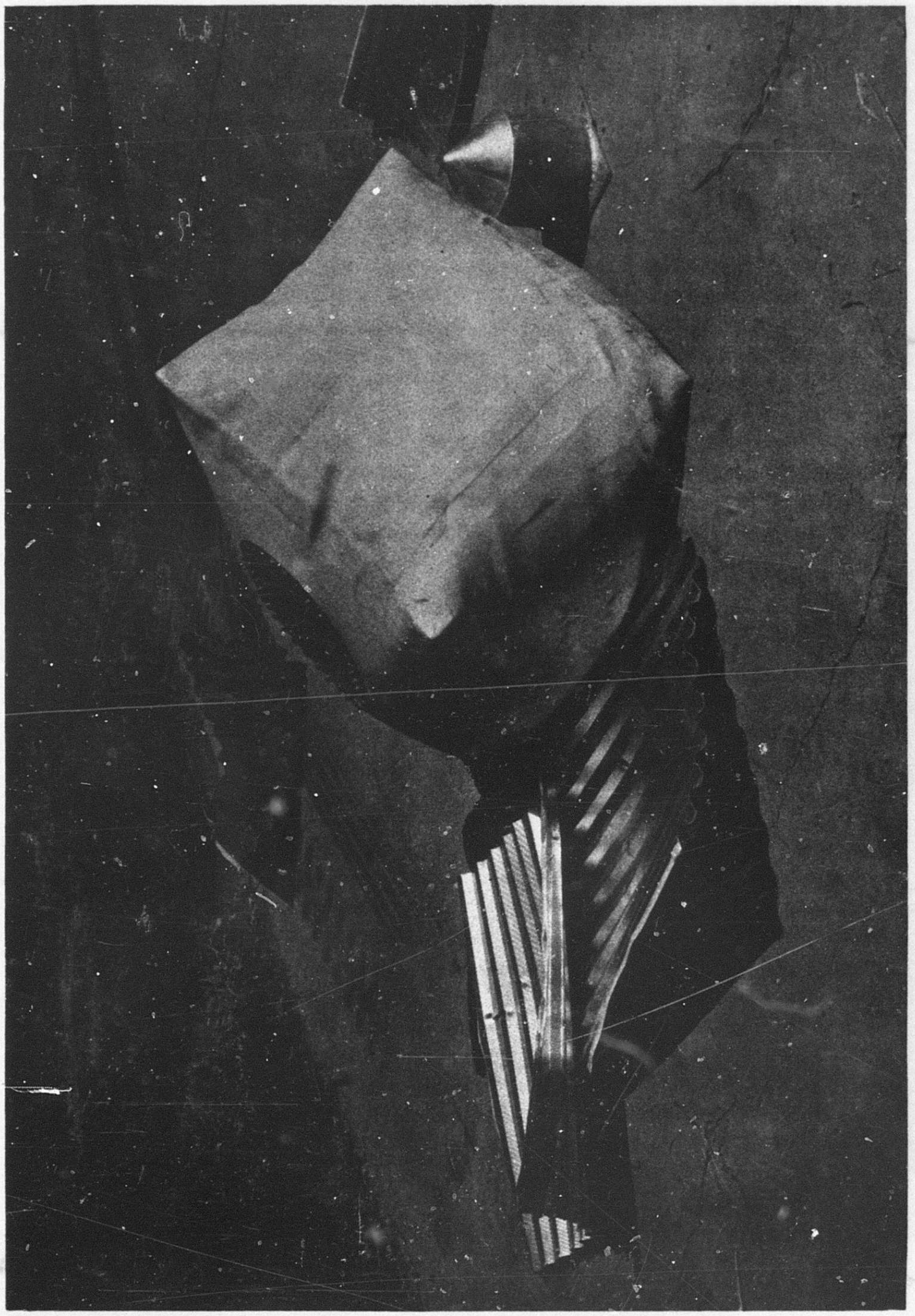


Figure 29. Cube Tank Drop Test.

the tank had expended energy by ground contact after draping around the anvil. This same tank was dropped a third time. The third drop was from a 15-foot height onto a much more severe anvil (Figure 30). The anvil was a 4-inch-diameter tube tipped with a 45-degree cone having a 1/4-inch-diameter flat point. Penetration was anticipated and achieved on this drop. The purpose of the test was to determine the ability of the ARM-021 construction to limit progressive tearing when subjected to the combined forces of penetration and hydraulic pressures at impact. The penetration did not cause progressive tearing of the tank bottom. The reverse actually occurred when there was sufficient fiber displacement surrounding the penetration locus to permit constrictive closure of the tank around the anvil. This closure was tight enough to grasp and hold the heavy anvil as the tank was lifted from the ground. Leakage around the anvil in this hoisted position was minimal.

Another ARM-021 tank was fabricated using eight-ply bottom and five-ply sidewall and top construction. The 30-inch-square by 24-inch-deep configuration was maintained. However, the test anvil was modified to preclude ground contact of the tank at impact. The 90-degree by 8-inch-diameter conical anvil used previously was mounted on a pedestal to increase the over-all height to 24 inches (Figure 31).

This tank was filled to capacity with 770 pounds of water and dropped from a height of 8 feet above the apex of the anvil. High-speed movie coverage taken during the test showed that all of the energy was expended on the cone with no ground contact. No damage to the tank was sustained. This same tank was redropped on the anvil from a height of 14 feet above the cone, and penetration occurred.

Permeability Tests

Permeability rates were determined on the ARM-018 laminates with and without fuel barrier films. Four test fluids were used: JP-4, JP-5, aviation gasoline, and MIL-S-3136 type III test fluid (see Table V). The same fuel barrier film used on the ARM-018 was applied to the ARM-021 construction. Permeability rates for ARM-018 and ARM-021 are therefore identical.

These tests followed the procedure outlined in MIL-T-5578C.

Test Results

The permeability-diffusion rates for the materials tested are shown in Table V. Values are based on an average of three specimens for each test.

Figure 30. Drop Test Anvil (45 Degrees, 4-Inch Diameter, 15 Inches High).

Figure 31. Drop Test Anvil (90 Degrees, 24 Inches High).

TABLE V
PERMEABILITY TEST

Average diffusion rates are in fluid ounces per square foot per 24 hours.

Materials Tested	JP-4	JP-5	Aviation Gasoline	MIL-S-3136 Type III Test Fluid
ARM-018 W (without film barrier) unfolded	-	-	0.021	-
ARM-018 W (without film barrier) folded	-	-	0.105	-
ARM-018 Y (without film barrier) unfolded	-	-	0.075	-
Nylon film (barrier only)	0.008	0.008	0.008	0.008 - 0.010
ARM-018 W (with film barrier) before folding	0.008	0.007	0.007	0.007 - 0.009
ARM-018 W (with film barrier) after folding	0.008	0.007	0.009	0.008 - 0.009
Standard sprayed coating (nylon-urethane)	-	-	-	0.019 - 0.020

Analysis of Results

Tests conducted on the base ARM-018 W and Y laminates showed the W resin to be satisfactory, while the Y laminate showed excessive permeability. However, after being subjected to a double-fold test, the W laminate also showed excessive loss. Other tests on ARM-018 W laminates (cylindrical tank impacts and the

air-gun tests) gave substantiating evidence that when the laminate is highly stressed, the continuity of the elastomer bond breaks down and leaves a permeable structure. From these results, it became evident that a barrier film would be needed.

When a 0.002-inch nylon barrier film was added to the laminate, the permeability rates were greatly reduced. Samples subjected to the double-fold test still showed no appreciable increase in permeability. The tests gave ample evidence that the nylon film barriers were capable of meeting the permeability requirements set by MIL-T-5578, even under high stress conditions.

FUEL AND OIL ABSORPTION TESTS

Fuel and oil absorption of the ARM-018 W construction was tested in accordance with MIL-P-8045B and Federal Test Method Standard 406. Fuel and oil absorption tests were not performed on the ARM-021 construction. These tests are not applicable to the ARM-021 since they apply primarily to fuel and oil tank plastic backing materials. ARM-021 is not suitable for this use.

Test Results

The percentage of weight change caused by fuel absorption and by immersion in oil is presented in Tables VI and VII.

TABLE VI

FUEL ABSORPTION

7 Days, 75 Degrees F	
W type standard elastomer content (35-40 percent)	Average weight increase (percent) 3.73
W type low elastomer content (20-23 percent)	Average weight increase (percent) 4.70

TABLE VII

OIL ABSORPTION

7 Days, 75 Degrees F	
W type standard elastomer content (35-40 percent)	Average weight increase (percent) 2.43
W type low elastomer content (20-23 percent)	Average weight increase (percent) 7.85

Analysis of Test Results

The fuel absorption rates of both the standard and the low elastomer content samples were well below the 6-percent weight increase allowed by MIL-T-8045B. The oil absorption rate of the standard samples (with 35- to 40-percent elastomer content) was very low but increased rapidly as the percentage of elastomer decreased.

The oil absorption tests were conducted for general property definition only, since the temperature limitations of the ARM-018 material prohibit its use as an oil tank lining.

AGING TESTS

The effect of long-term aging at three elevated temperatures and also long-term soaking in aviation gasoline and JP-4 and JP-5 fuels was evaluated using tensile and lap shear adhesion samples. Both the tensiles and lap shears were tested at 75 degrees F following exposure periods of up to 180 days. Test procedures were identical to those employed for regular tensile and lap shear tests.

Unconditioned samples were tested initially, and the remainder of the samples were placed in 110-, 160-, and 215-degree F ovens and in containers of aviation gasoline and JP-4 and JP-5 fuels maintained at 75 degrees F. Both the tensile and lap shear tests were performed using an Instron testing instrument. The maximum crosshead rate of 20 inches per minute was used with a 3-inch specimen gage length. A sample strain rate of approximately 6.6 inches per inch per minute was therefore achieved.

Tensile and lap shear tests were performed for both heat aging and fuel soaking on the ARM-018 W elastomer system at all exposure periods. Lap shear tests only were performed on the X, Y, and Z elastomer systems for all heat aging and fuel soaking exposure periods. Tests did not include the ARM-021 construction since the same elastomer system is used.

Test Results

The results of these aging tests are graphically presented in Figures 32, 33, 34, 35, 36, and 37.

Analysis of Test Results

Tensile strength degradation appears to be most affected by temperatures over 160 degrees F. Long exposure at 110 degrees F seems to have no effect on tensile strength, but 215 degrees F exposure quickly causes strength reduction. The rate of loss at 215 degrees F seems to stabilize somewhat after approximately 10 days. Soaks of up to 180 days in aviation gasoline and JP-4 and JP-5 fuels at 75 degrees F did not cause a reduction of tensile strength.

All four elastomer systems showed a significant initial increase in bond strength at all elevated temperatures. This beneficial influence was apparently caused by a phase of the post cure and appears to have continued for about 10 days, after which further exposure caused a reduction of bond strength. The post curing had the greatest effect on the W elastomer system, nearly doubling the original bond strength prior to the onset of degradation.

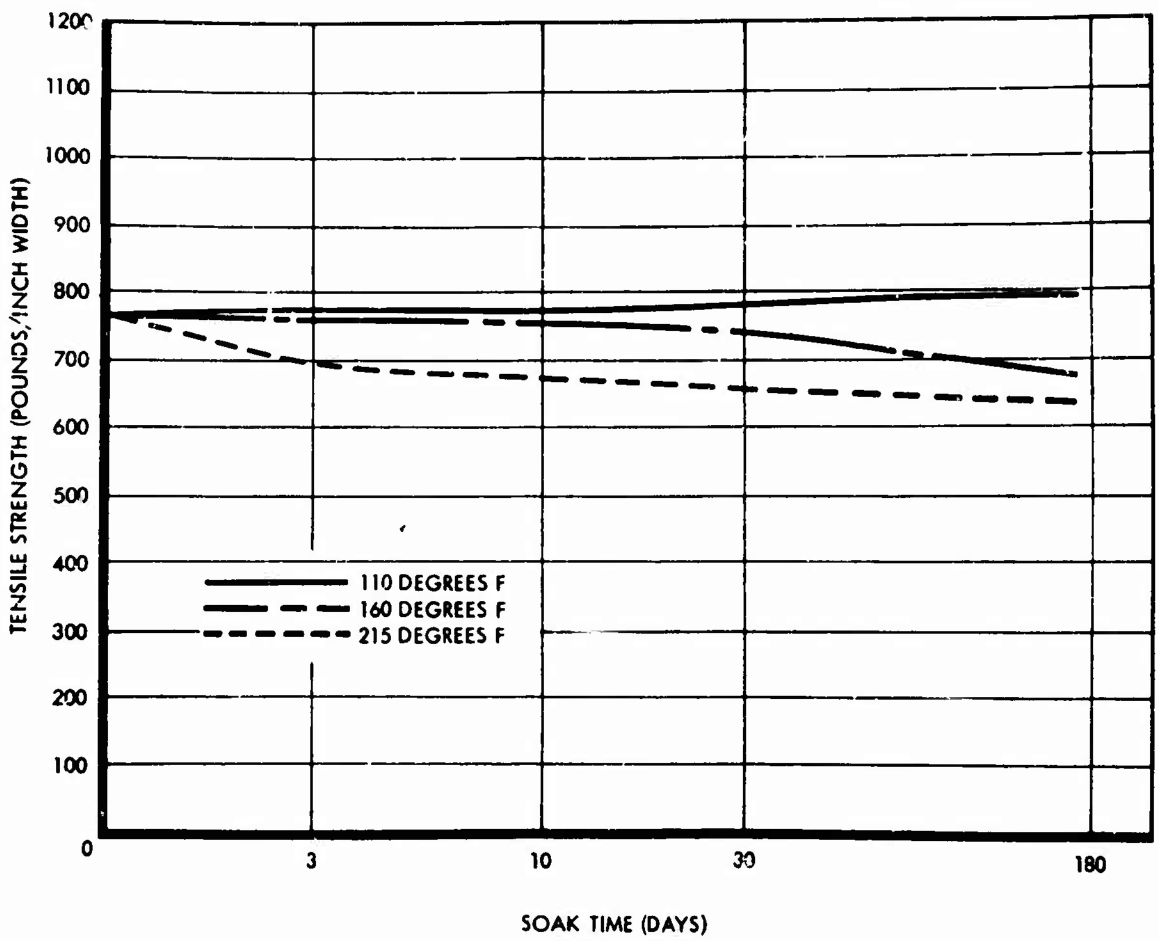


Figure 32. High Temperature Tensile Aging (W Resin, 20 Inches/Minute).

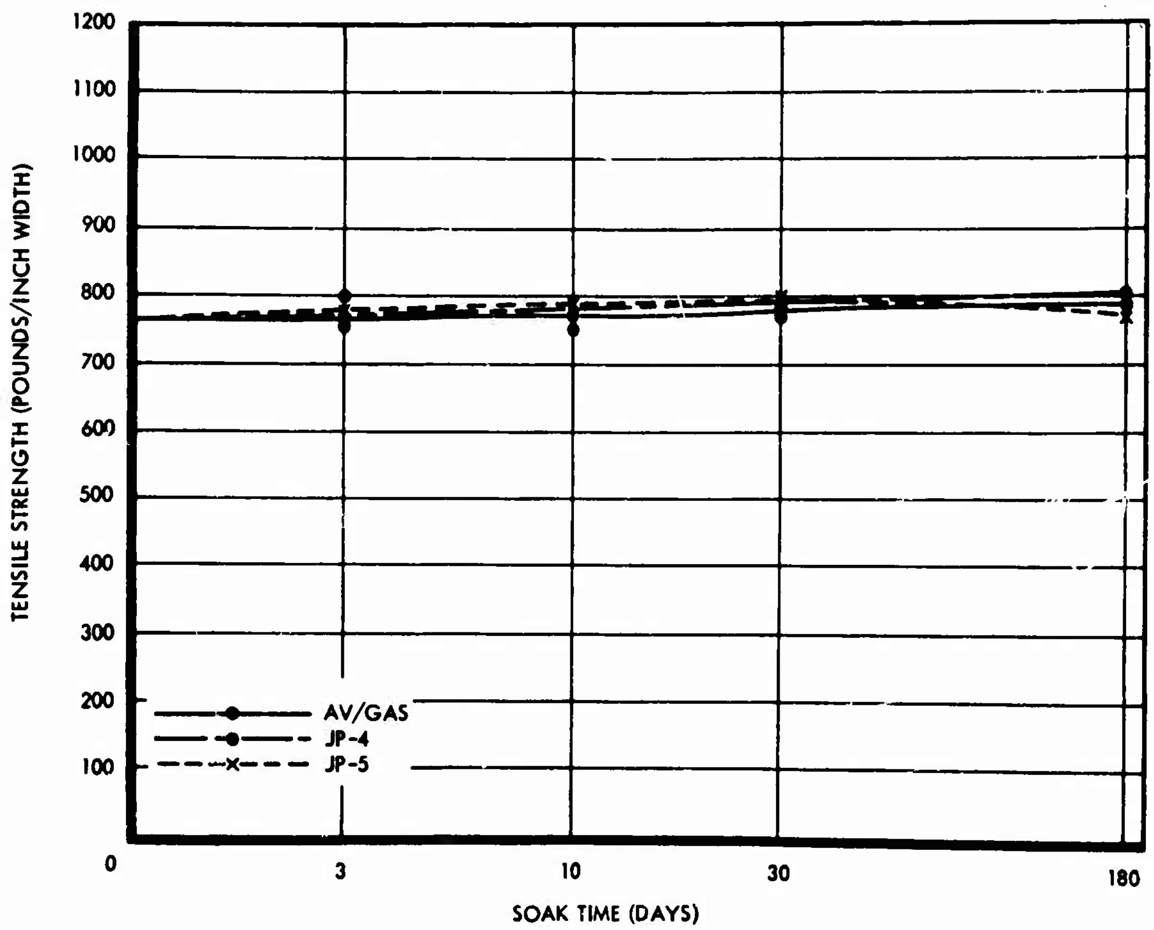


Figure 33. Fuel Soak Tensile Aging (75 Degrees F, W Resin, 20 Inches/Minute).

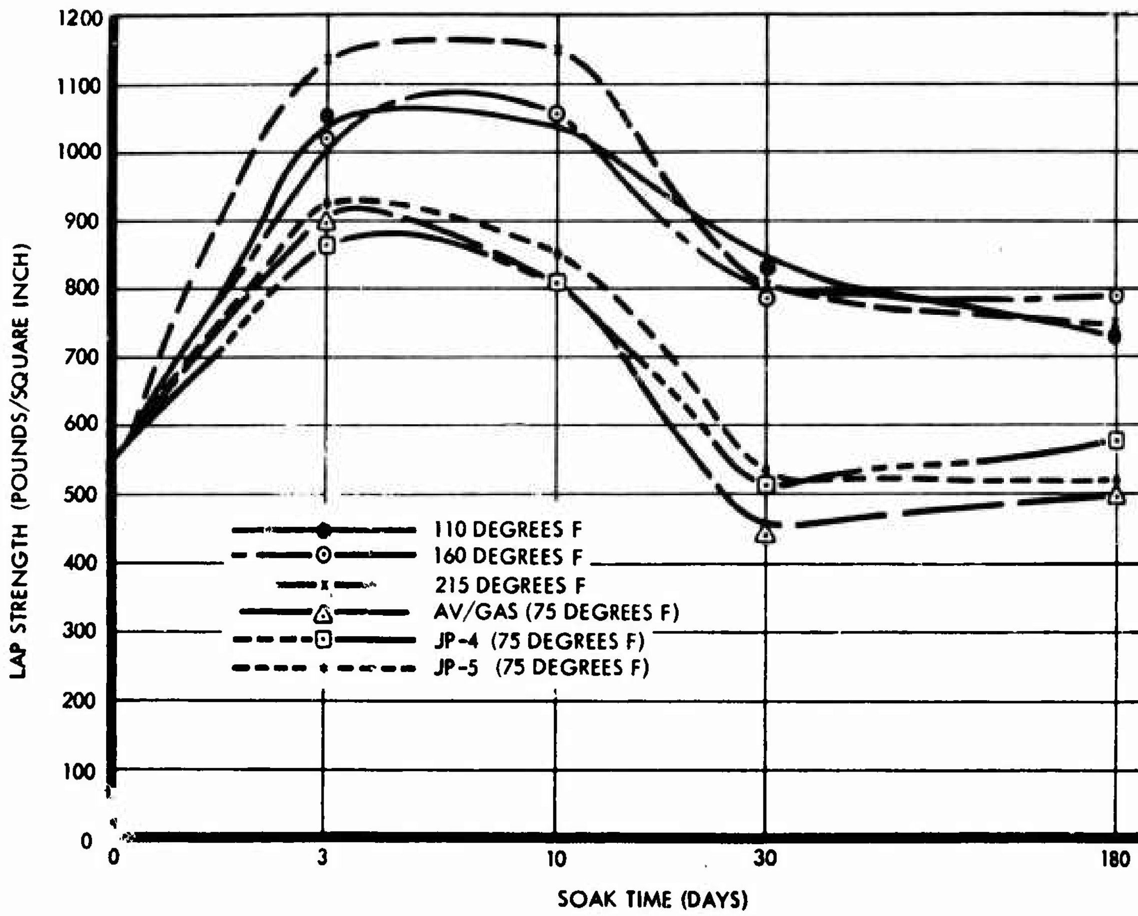


Figure 34. Heat and Fuel Soak (W Lap Shear)

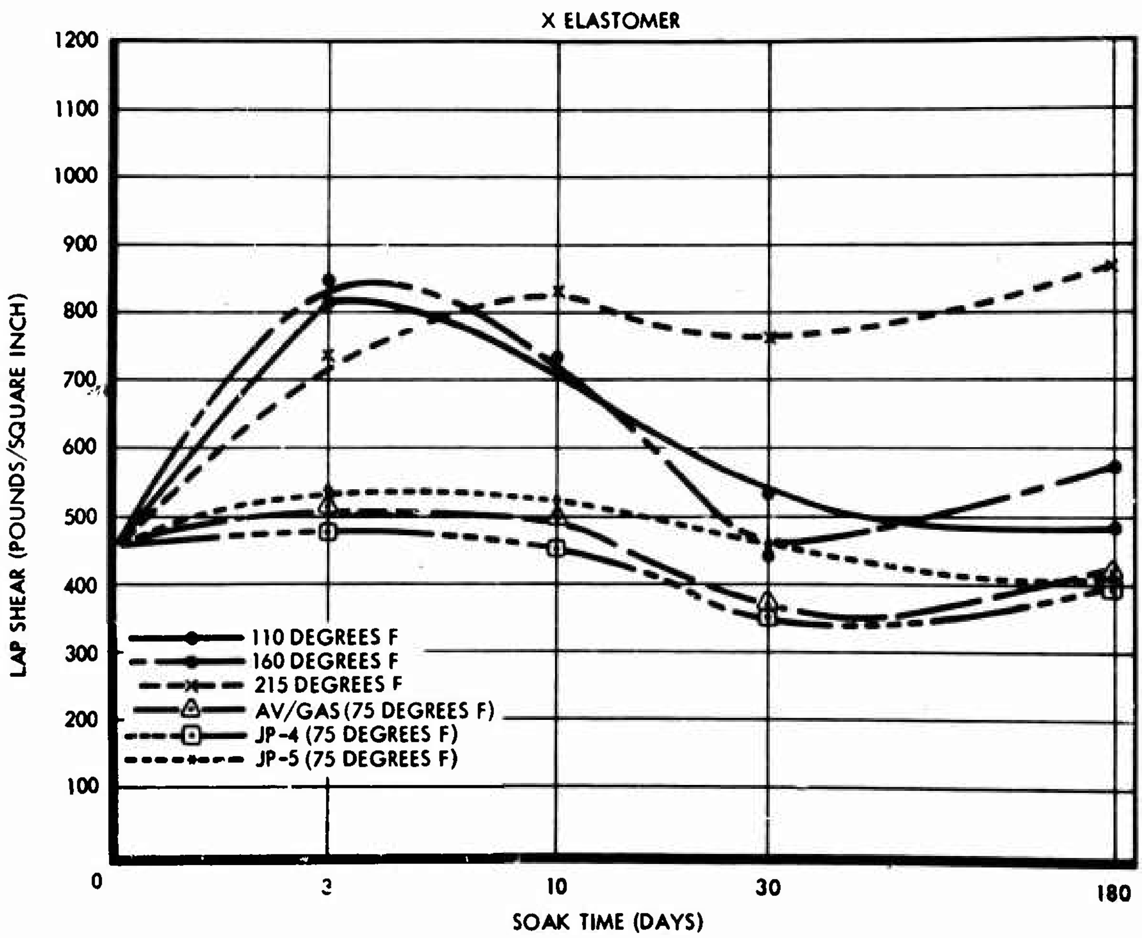


Figure 35. Heat and Fuel Soak (X Lap Shear).

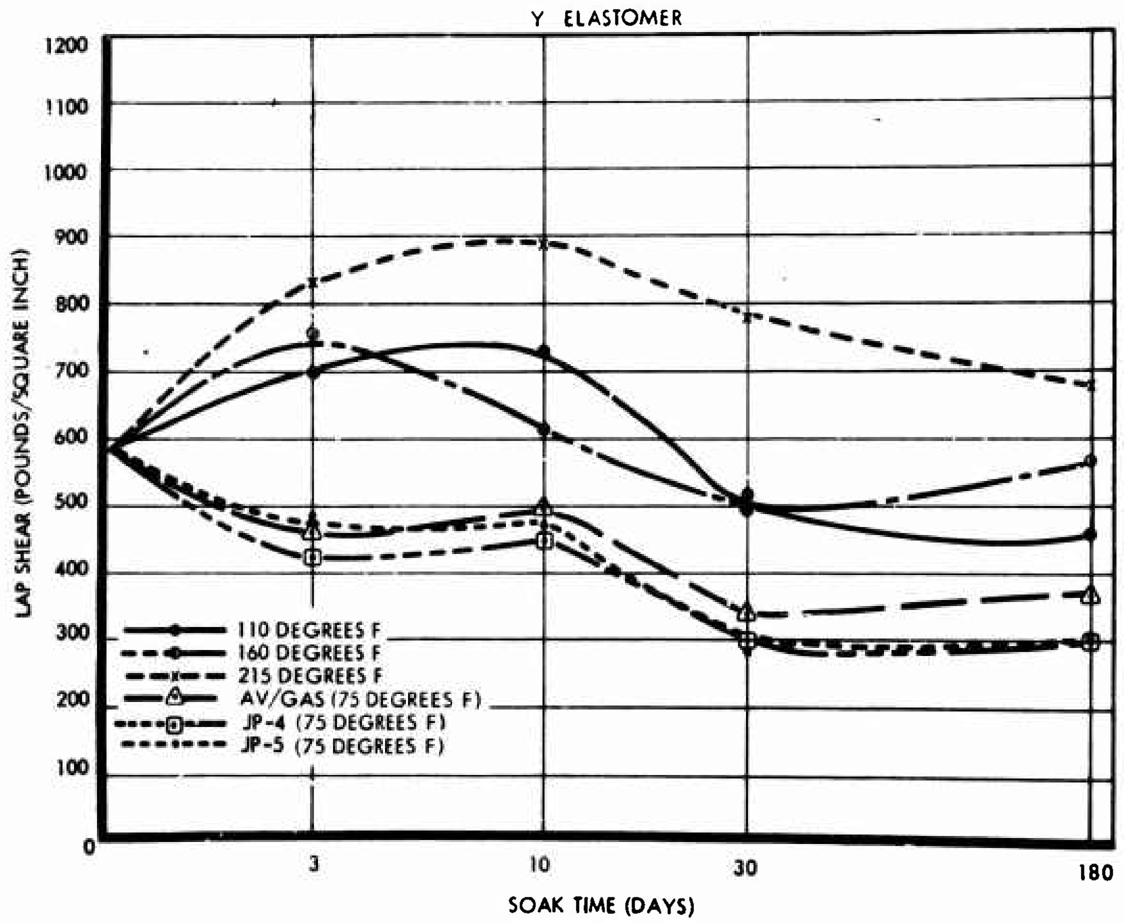


Figure 36. Heat and Fuel Soak (Y Lap Shear).

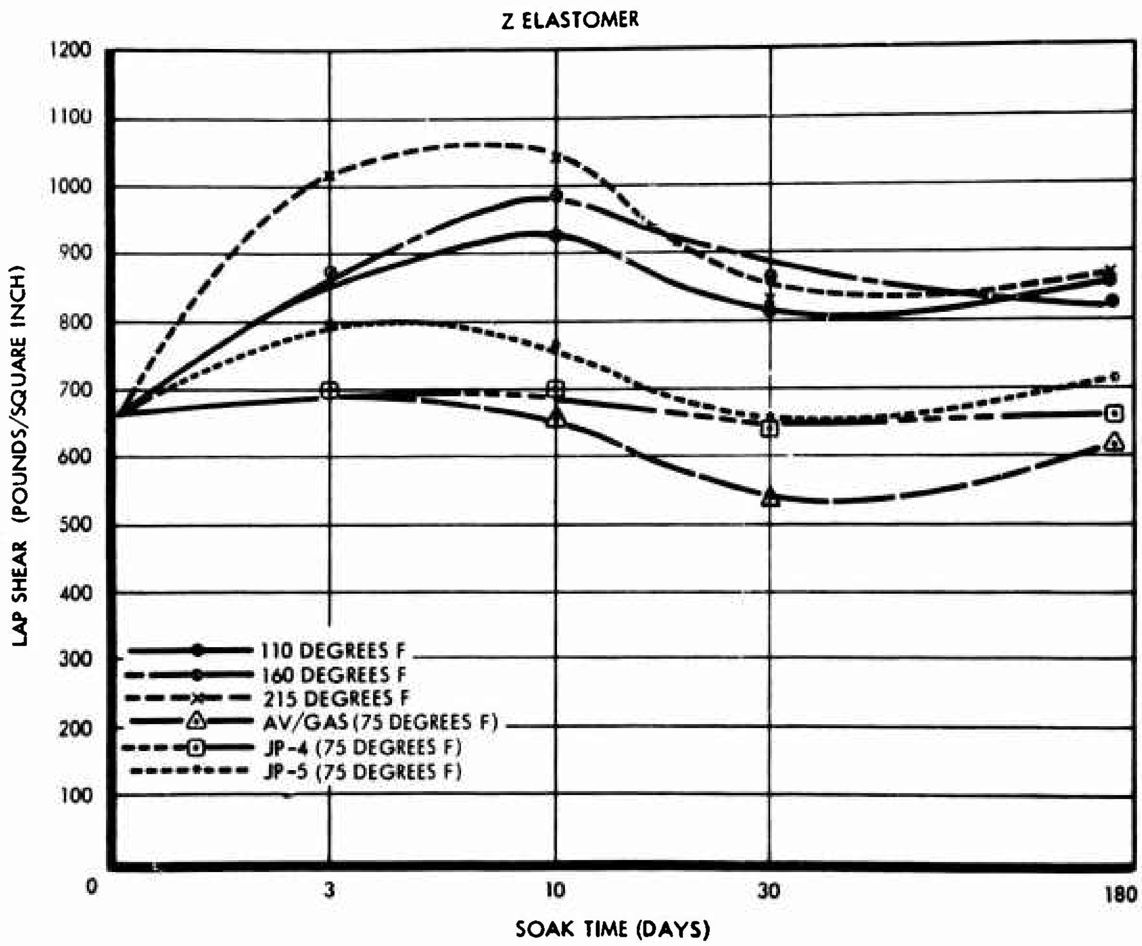


Figure 37. Heat and Fuel Soak (Z Lap Shear).

The post cure is also noticeable at 75 degrees F on the urethane elastomer systems (W and Z) soaked in fuel. Again, the bond strengths dropped after 10 days to approximately the original bond strength, thus showing no significant degradation of the bond by the fuel. The polyether elastomer systems (X and Y) showed no indication of post-cure bond strengthening when soaked in the fuel, although the heat aging tests did indicate that post cure was occurring. All three fuels evidently degraded the bond strengths of these elastomers rapidly enough to negate post-curing effects. This degradation is especially apparent for the Y elastomer, where the bond strength after 180 days' soaking time was only 50 to 60 percent of the original strength.

TEMPERATURE-HUMIDITY RESISTANCE TESTS

The temperature and humidity tests were performed using 1-inch-wide peel samples. Original control peel tests were performed on both the samples which were to be conditioned and the duplicate samples not to be conditioned. The duplicate samples were tested for control purposes each time tests were run on the conditioned samples. Samples of ARM-018 were fabricated for this test using the 4 elastomer systems. Samples of ARM-021 construction were not tested since identical basic materials are used.

Conditioning was performed at 125 degrees F and 98-percent relative humidity, with tests being run following 8, 30, 60, and 100 days' exposure. Samples were tested immediately following removal from the conditioning chamber.

Samples were peeled at a 20-inch-per-minute machine crosshead rate, giving a linear peel rate at the bond line of 10 inches per minute. Autographic record of the test was made, and the average peel strength for each sample was calculated.

Test Results

The temperature-humidity resistance test results are shown in Figure 38.

Discussion of Results

As shown in Figure 38, the peel strength of the W and Z elastomer laminates showed considerable degradation from humidity effects, even at 125 degrees F.

No attempt was made to coat or otherwise protect the cut sample edges. This, plus the relatively narrow sample widths, undoubtedly allowed much greater moisture absorption into the bond than would be possible in a typical fuel cell application. However, it is evident that the polyether urethanes, especially the Y polymer, show far better resistance to high humidity than do the polyester urethanes.

These tests are continuing, and values will be recorded over a 12-month period.

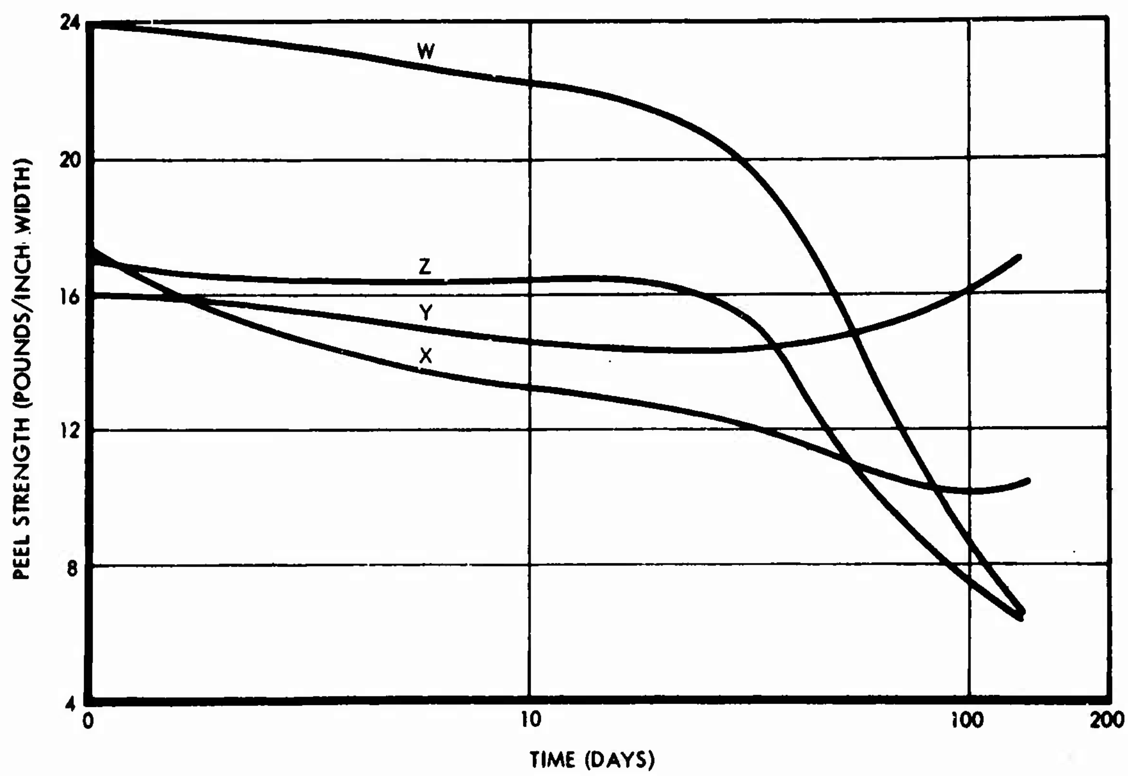


Figure 38. Temperature-Humidity Resistance (Peel Test-125 Degrees F, 98-Percent Relative Humidity).

FUNGUS RESISTANCE TESTS

The fungus resistance of the four types of ARM-018 was determined by the following method. Single-ply samples of the standard reinforcement were fabricated using all four elastomer systems. These samples were fabricated into individual test panels having a 0.50-inch primary bond lap. Ten 1-inch-wide lap shear samples were tested for fungus resistance as defined by MIL-STD-810A (USAF) Method 508.1. Samples of ARM-021 were not tested since it is constructed of the same basic materials as ARM-018.

The samples were subjected to a mixed spore suspension of chaetomium globosum ATCC 6205, aspergillus niger ATTCC 6275, aspergillus tamarii (A. flavus) ATCC 10836, and penicillium ochrochloron ATCC 9112 at 30 degrees C for 28 days.

Test Results

Visual examination following this exposure showed no mold growth or evidence of deterioration of any sample of the four elastomer systems (Appendix II, Certification of Outside Tests for Fungus Resistance).

These lap shear samples were then tested, with no reduction of bond strength being found for any of the four elastomer systems.

Analysis of Results

All applicable military specification requirements for fungus resistance were met.

FUEL CONTAMINATION TESTS

Fuel contamination tests were performed on all four ARM-018 elastomer systems laminated with the standard reinforcement. Contamination of aviation gasoline, JP-4 and JP-5 fuels, and test fluid conforming to Specification TT-S-735, Type III, was determined using test methods conforming to MIL-T-5578 and Federal Test Method Standard 791. Samples of ARM-021 were not tested since it is constructed of the same basic materials as ARM-018.

Test Results

The results of the fuel contamination tests are presented in Table VIII.

Analysis of Test Results

The results indicate that the contamination of the four test fluids was negligible for all four elastomer systems.

TABLE VIII
ELASTOMER FUEL CONTAMINATION (MILLIGRAMS PER 100 MILLIMETERS)*

	Average Gas		JP-4		JP-5		TT-S-735 Type III Fluid	
Elastomer System	Gum Content	Stoved Gums	Gum Content	Stoved Gums	Gum Content	Stoved Gums	Gum Content	Stoved Gums
W	0.006	0.005	0.008	0.005	0.005	0.004	0.005	0.004
X	0.006	0.005	0.009	0.008	0.013	0.001	0.006	0.004
Y	0.009	0.008	0.007	0.005	0.018	0.002	0.0157	0.004
Z	0.004	0.003	0.014	0.008	0.003	0.001	0.004	0.002

*Results are corrected for preformed gum in each test fluid.

FUEL FITTING ATTACHMENT TESTS

A series of tests was performed to evaluate the ability of the three ply ARM-018 laminate to resist fitting tearout. All test samples were fabricated using the W elastomer system with the standard elastomer content (35 to 40 percent) and 90-degree reinforcement ply orientation. An evaluation was made of tearout resistance of several sizes of fittings. Simulated fittings were tested in 7/8-inch and 3-inch diameter and in 5-1/2-inch by 7-inch oval-shaped holes. The effect of adding a circular four-ply nylon doubler around the hole was investigated. The doubler diameter was 8 inches for the 3-inch hole samples and 6 inches for the 7/8-inch hole samples. The oval samples were tested without doublers.

The load was applied in several modes, the first being a straight tensile pull (Figure 39), while a cross-axis tearout was also used (Figure 40).

The simulated fittings used in the straight tensile pullout were neither bonded nor bolted to the laminate to permit better determination of the tearout resistance of the laminate. The fitting was fastened to the cross-axis tearout samples with six bolts. The fittings were pulled at a machine crosshead rate of one inch per minute. Tests were performed on 3-inch-diameter hole samples with both loading modes, doubled and undoubled, at -65, 0, 75, and 160 degrees F. Tests on the doubled and undoubled 7/8-inch-diameter hole and on the oval hole samples were run only at 75-degree temperature. The ARM-021 construction was not tested for fitting attachment strength, as this construction is impregnated to ARM-018 elastomer content in the attachment area for added strength.

Fuel fitting tearout test results are shown in Figures 41 and 42.

Analysis of Test Results

The importance of a potential crash-resistant fuel cell material with the strength to resist fitting tearout has been well documented in actual crash histories. Rigid tank-to-structure attachments have been shown to be a common failure point in a crash environment.* Undoubtedly, the cross-axis fitting tearout most closely simulated the combined forces acting on an attachment during a crash. Failure modes of the attachment bolt holes through the laminate show the importance of bearing strength to over-all performance (Figure 43).

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*S. Harry Robertson and James W. Turnbow, Ph.D., Aircraft Fuel Tank Design Criteria, USAAVLABS Technical Report 66-24, March 1966, pp. 10 and 11.

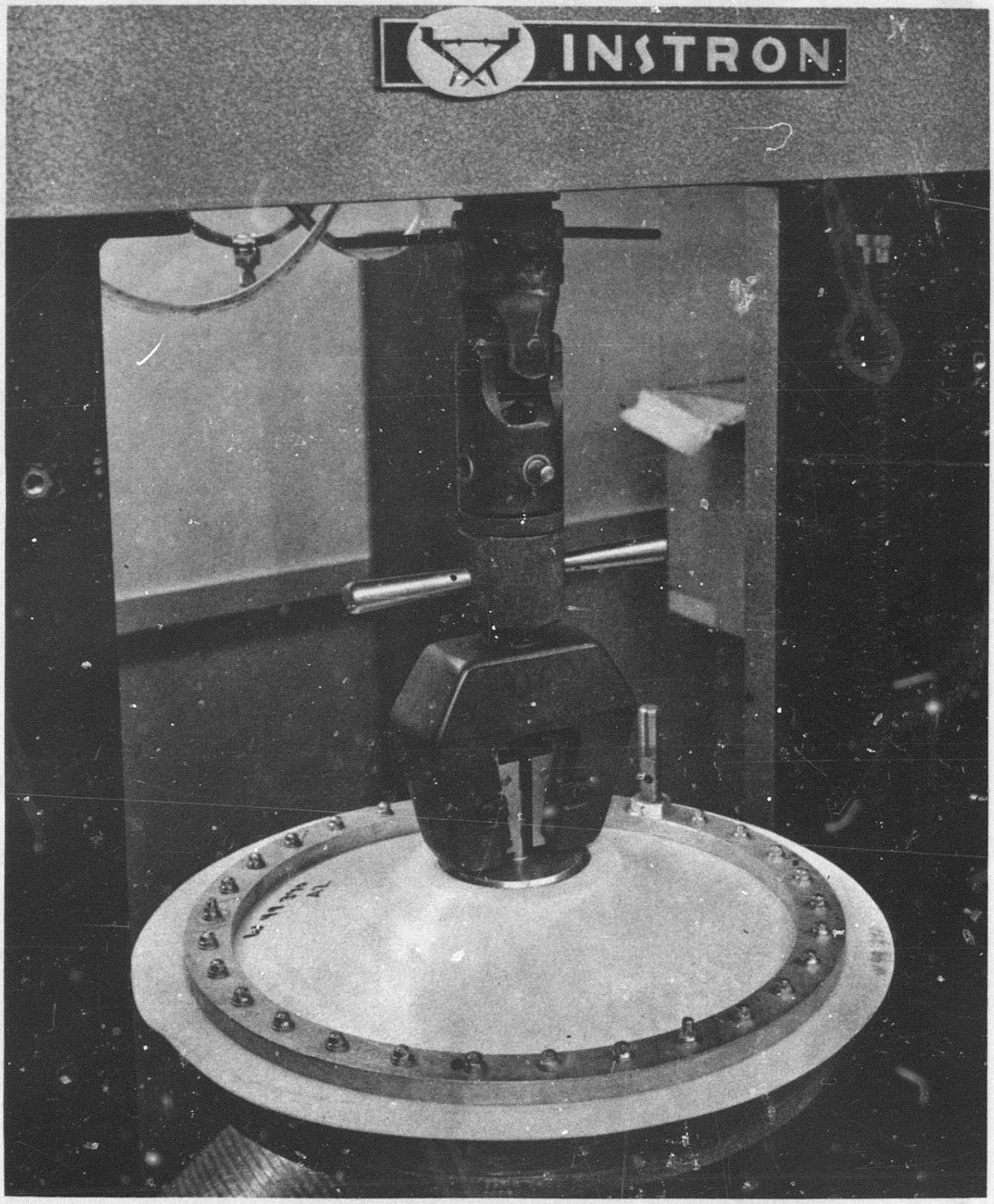


Figure 39. Tensile Fitting Tearout.

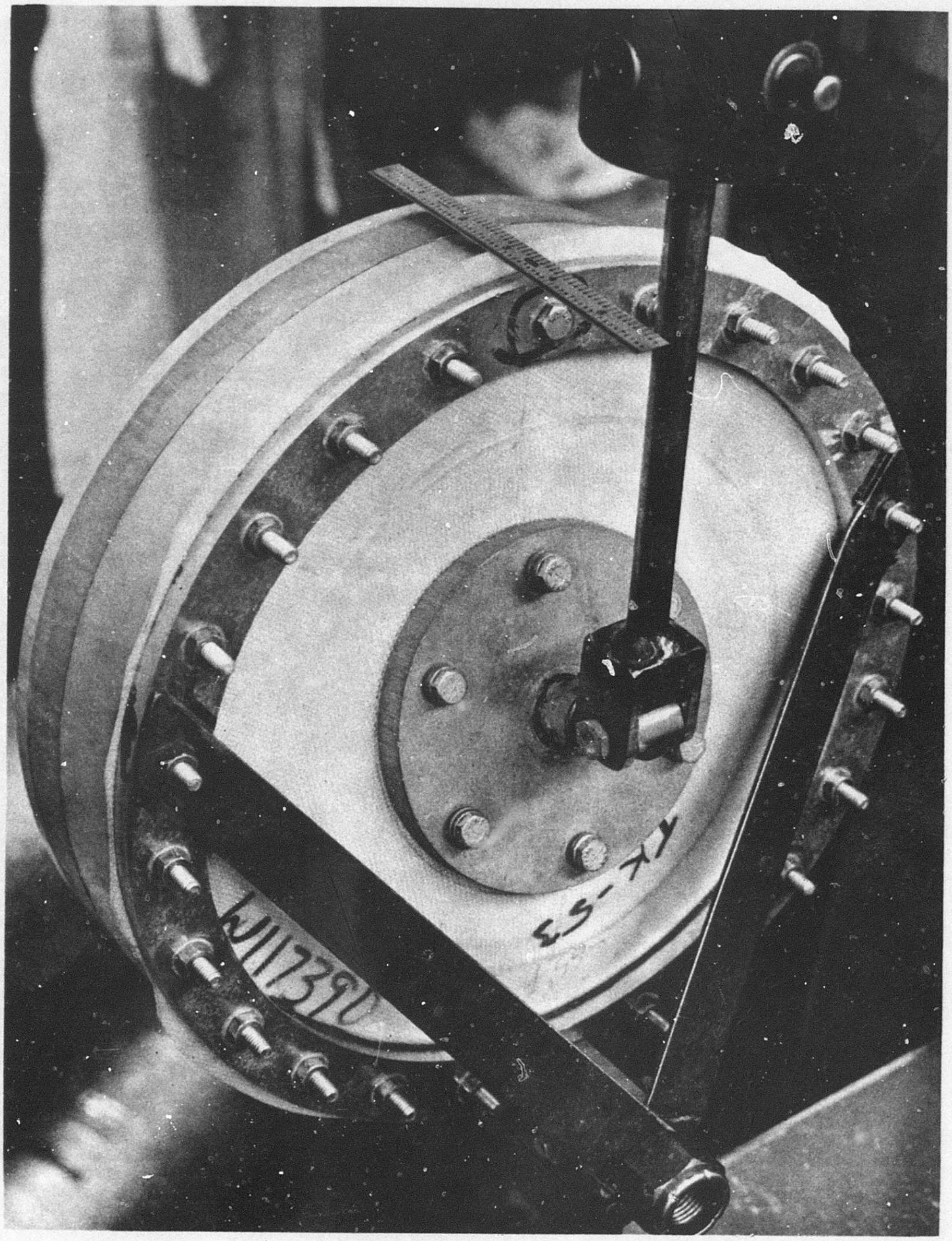


Figure 40. Cross-Axis Fitting Tearout.

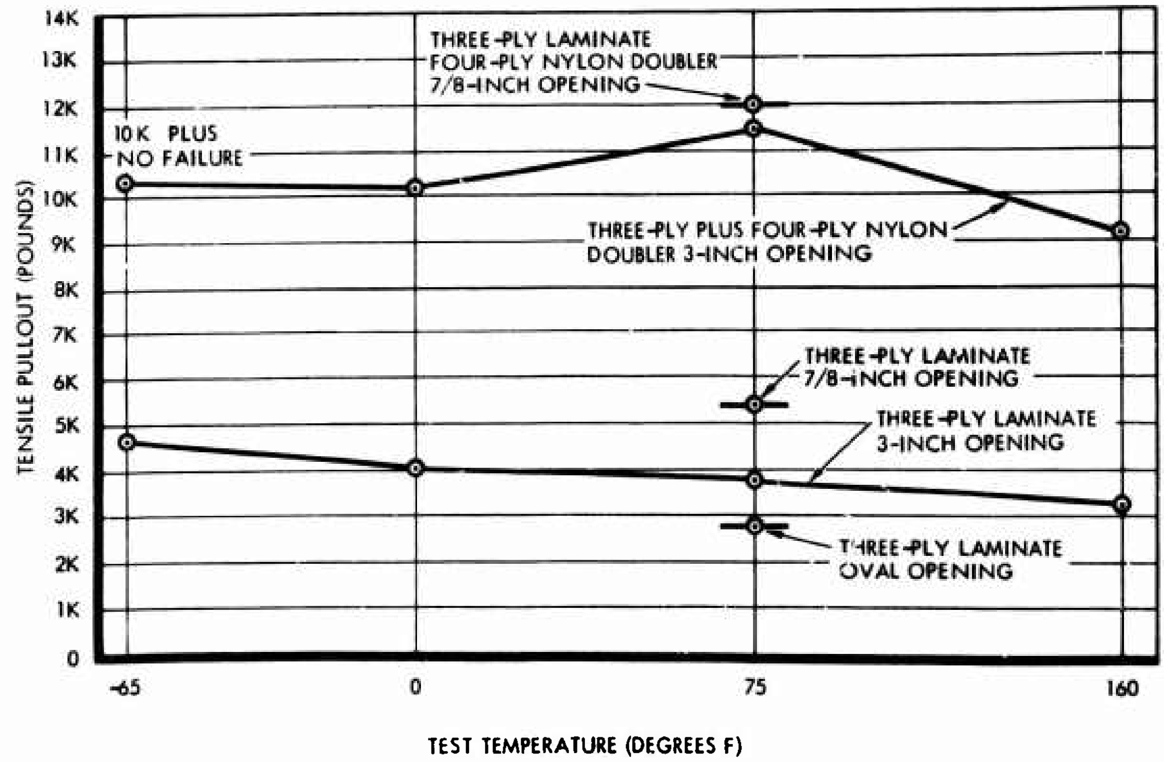


Figure 41. Fuel Fitting Tensile Tearout.

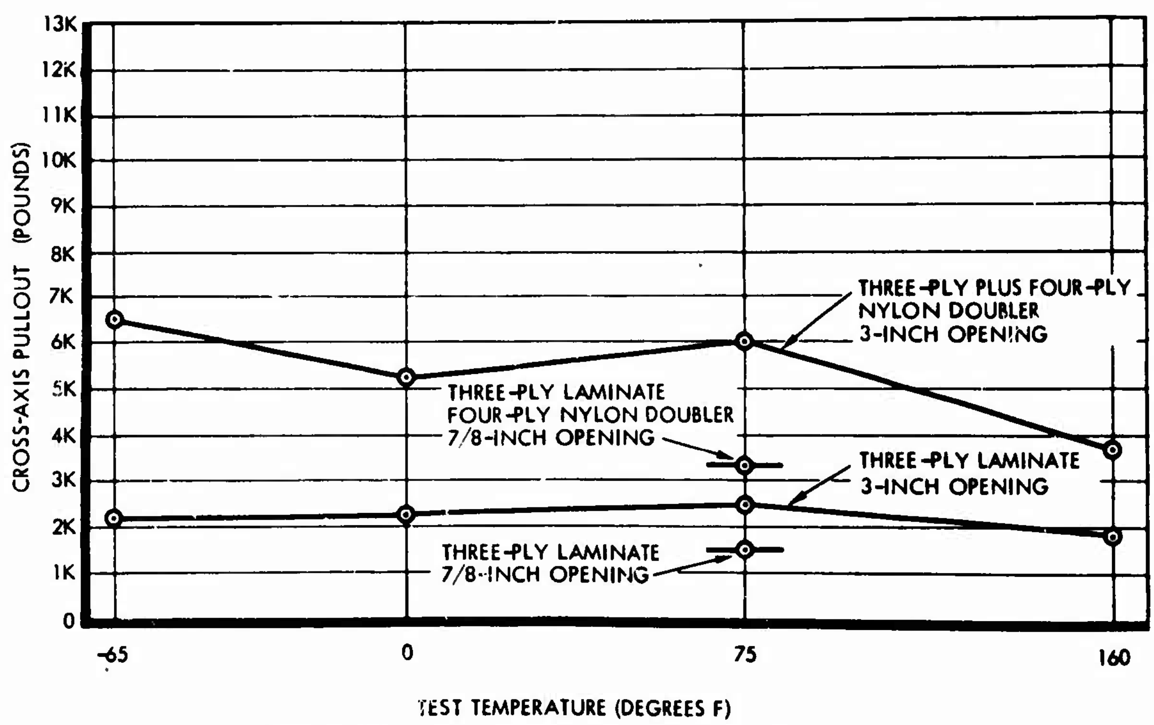


Figure 42. Fuel Fitting Cross-Axis Tearout.

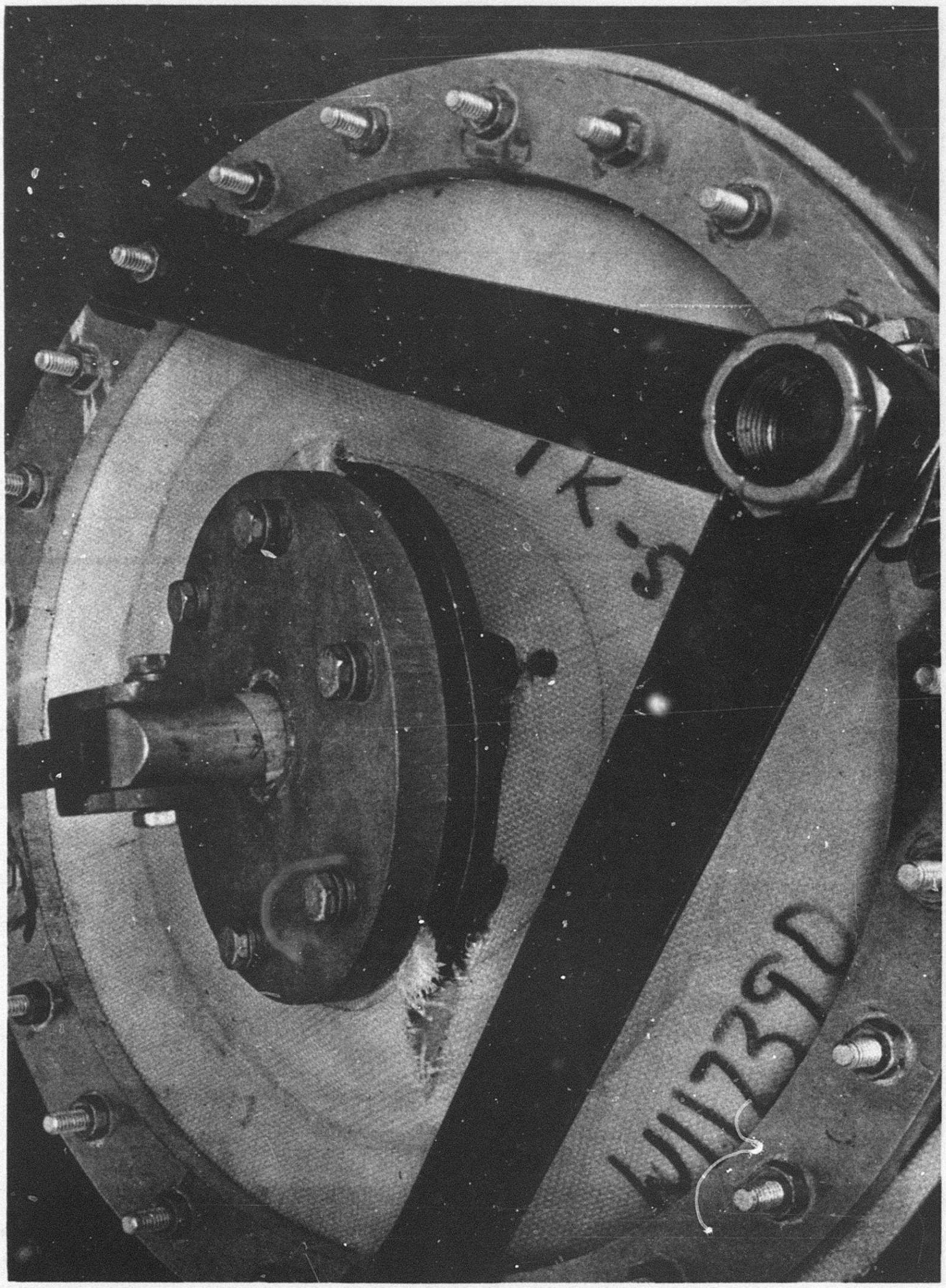


Figure 43. Cross-Axis Fitting Failure Detail.

The results of these tests indicate that the ARM-018 W elastomer laminate far surpasses all current specification requirements for fitting tearout strength. The addition of the four-ply nylon doubler to the attachment area yields significant additional tearout resistance.

FITTING PRESSURE LEAK TESTS

A three-ply sample made with the W elastomer system was prepared to fit the circular holding fixture previously used in the tensile fitting tearout test series (Figure 44). A simulated fitting was bonded with the W elastomer and also fastened with six bolts. The fitting was mounted through a 3-inch-diameter centrally located hole. The entire sample was then mounted in the test fixture, again using the W elastomer and bolts. After curing, the assembly was filled with water through a pressure fitting which was installed through the backing plate assembly. The assembly was pressurized at 10-psi increments to the full available line pressure of 110 psi. The assembly was carefully checked for leakage at each pressure increment.

Test Results

No evidence of leakage was found at the bonded fitting, and no water permeated the ARM-018 W membrane.

Analysis of Test Results

Leakage from bonded and bolted fitting attachments does not appear to be a problem. The pressure sustained by the test fitting far surpassed existing operational fuel system pressures.

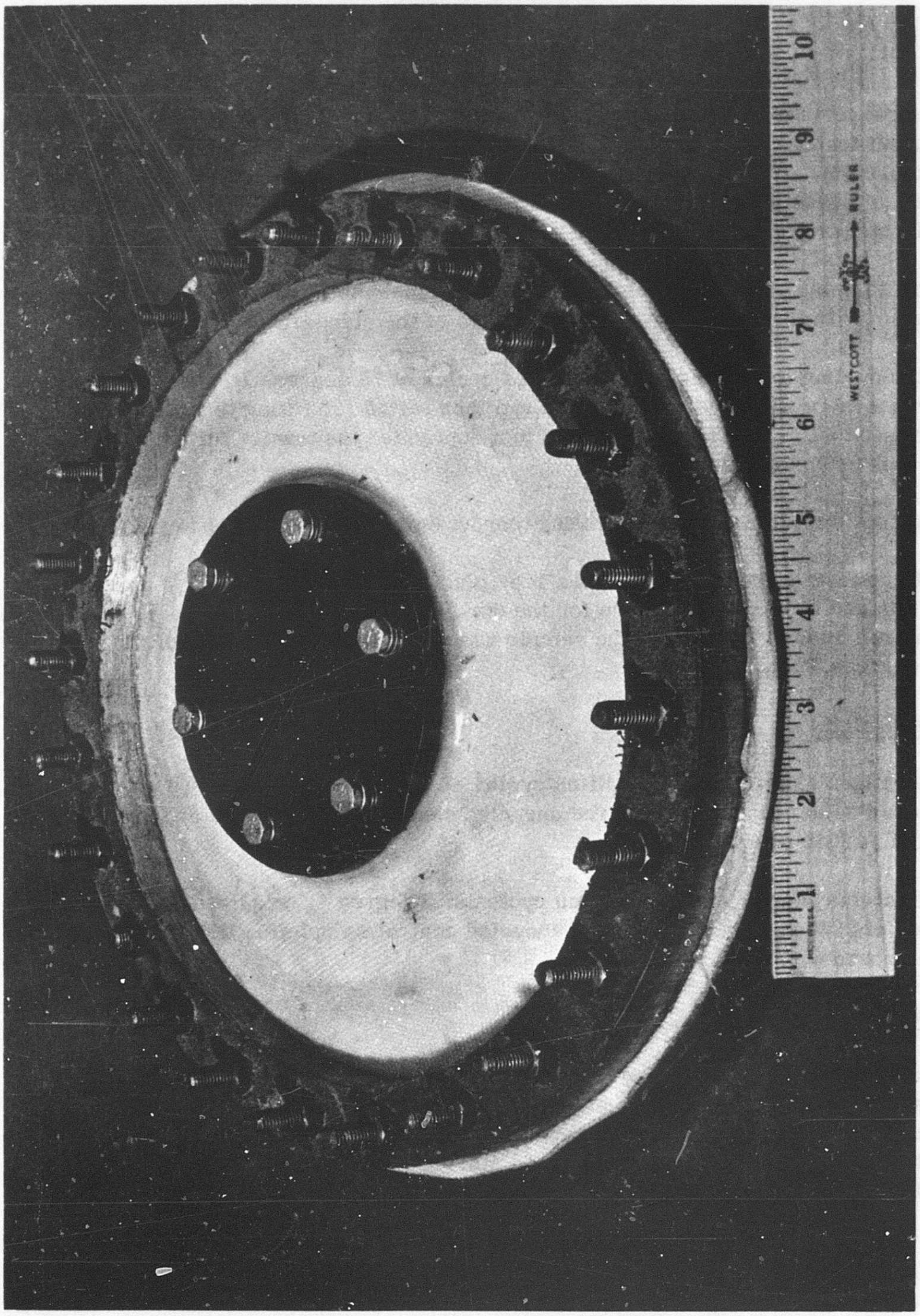


Figure 44. Fitting Leak Test Assembly.

FATIGUE TESTS

Fatigue tests were performed by modifying the fixture used in the tensile fitting tearout test series to accommodate mounting the sample in a cyclic tester (Figure 45). When so mounted, the oval-type fitting was subjected to a displacement of 0.060 inch by means of an eccentric throw. The cycling rate was set at 1800 cycles per minute.

Test samples used for this test series were fabricated using the W elastomer system with three 60-degree oriented plies of the standard reinforcement.

After cycling for a specified number of cycles at 75 degrees F, the sample was given a thorough visual examination and then tested for fitting tearout in the same fixture. This final evaluation test duplicated the tensile fitting tearout tests previously described.

Controls were run for tensile fitting tearout on samples identical to those cycled.

Fatigue tests were run at 0 degree F by placing the cyclic tester in a chamber maintained at this temperature for the duration of the test. Upon completion of the required number of cycles, the sample was examined and tested to destruction at 75 degrees F.

Test Results

The fatigue sample, run 39 million cycles at 75 degrees F, required a tensile force of 3130 pounds to fail. The uncycled control sample tested at this time failed at 2950 pounds.

The fatigue sample, run 60 million cycles at 0 degree F, required a tensile force of 2760 pounds to fail. The uncycled control sample for this test failed at 2940 pounds.

Analysis of Results

After cycling for 39 million cycles at 75 degrees F, no delamination or other degradation was evident. Sample performance, when tested for tensile fitting pullout, was 6 percent greater than the uncycled control. The 0-degree F fatigue test was run for 60 million cycles, and a 6.0-percent reduction of strength was indicated by comparison with the control sample.

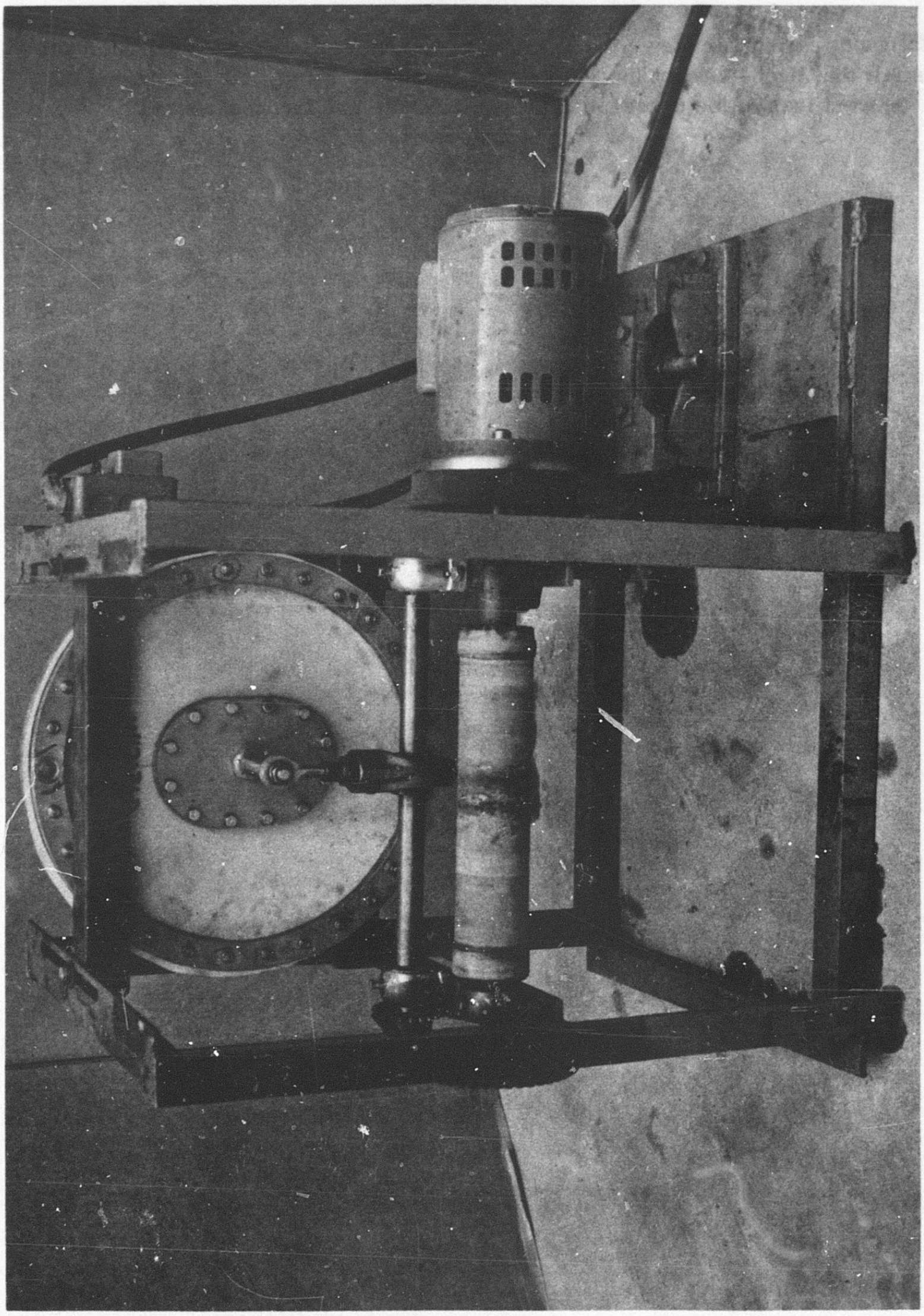


Figure 45. Fatigue Tester with Sample Mounted.

Unfatigued tearout samples showed a 12-percent spread in values. On this basis, it is felt that the 6-percent increase of the 75-degree F fatigued sample and the 6.1-percent loss of the 0-degree F fatigued sample are inconsequential.

CONCLUSIONS

1. The ARM-018 material has surpassed the requirements set by Specifications MIL-T-6396 and MIL-T-27422 for crash resistance and general performance. Although this material has some shortcomings in tensile strength to puncture resistance ratio, its over-all strength and energy absorption capability make it far superior to the materials currently used in crash-resistant fuel cells.

2. Of the four elastomers tested, the W and Y appear to be generally superior, although each of the four possesses certain properties superior to all others. The W elastomer is best for its chemical resistance, while the Y excels for its resistance to humidity effects and general performance under impact conditions.

3. The ARM-021 material is greatly superior to the ARM-018 in puncture and tear resistance. Its tensile strength-tear resistance ratio and tensile strength-puncture resistance ratio, combined with its light weight, establish this material as an excellent candidate for improved crash-resistant fuel cells.

4. A close correlation exists between the air-gun test values and the average tensile values based on single-ply fabrics tested at intermediate strain rates. The much higher strength of the ARM-018 material magnifies the difficulty of air-gun tensile edge retention encountered with currently used crash-resistant materials.

5. The drop tests using the large cube tanks appear to be excellent dynamic tests for qualitative evaluations of crash-resistant fuel tanks.

   a. The anvil drop test is designed to determine the ability of the tank material to resist penetration under the high loading rates and hydraulic pressures associated with crash impact. As a replacement for the air-gun test in Phase I (MIL-T-27422) qualification of cell materials, it would be superfluous because of the combined tensile, puncture, and tear tests which are designed to fulfill that function. However, as a Phase II (MIL-T-27422) type tank qualification test, it appears to be a most satisfactory method.

   b. The flat drop test, designed to determine the ability of the lap seams to withstand the hydraulic pressures and high onset loading rates at impact, also appears to be a very satisfactory Phase II (MIL-T-27422) type tank qualification test.

RECOMMENDATIONS

1. Further effort should be made to improve the elastomer in the ARM-021 material. Reformulation of the elastomer should be investigated to determine if the properties of both the W and Y elastomers could be combined in a single elastomer.

2. The following changes, described in detail in Appendix I, should be incorporated in Specification MIL-T-27422.

   a. The required fuel cell material strength should be increased.

   b. The air-gun tensile strength test should be replaced by more conventional tensile tests.

   c. Dynamic puncture resistance and tear resistance tests which more closely simulate impact conditions should be added to the Phase I qualification tests.

   d. Dynamic drop tests should be conducted as Phase II type qualification tests for crash resistant fuel tanks.

3. Additional experimental studies should be conducted to further define the basic properties of fuel cell materials, especially under dynamic loading conditions, to provide more detailed and realistic specification requirements.

APPENDIX I, SUGGESTED CHANGES FOR MIL-T-27422

Because of the considerable improvement of the ARM-021 material over conventional crash-resistant materials and because of deficiencies in standards of crash resistance found in MIL-T-27422, the following changes are recommended, based on an ARM-021 construction with ARM-018 construction in terminal areas.

3.7 Concentrated load tests conducted by AvSER and Goodyear Aerospace show that the values specified in this specification are wholly inadequate for survival limit crashes. A change suggested for this specification is that the equations used to calculate the required fuel cell material strength for both fuselage and wing cells be modified by increasing the values by a factor of 4. This formula should apply only to materials with a maximum elongation less than 25 percent.

4.5.1 The difficulty of air-gun tensile specimen edge retention, which poses a sizeable problem with currently used crash-resistant materials, is even more troublesome when testing the considerably higher strength materials being developed. Likewise, various pressure transducers have not proved to have reproducible accuracy, and calculations of strength and elongation are approximations at best.

The increased pressures necessary to burst the new high-strength materials are undesirable from a safety standpoint.

Because of these considerations, it is felt that greater reliability can be attained by the more conventional tensile tests. Specimens would be tested for biaxial values at a loading rate of 20 inches per inch per minute as a substitute for the air-gun tensile test. Tests by Goodyear Aerospace have shown the close correlation of the air-gun tensile test values to calculated values based on tensile tests of the individual reinforcement plies. These tests can be performed on existing test equipment with greater ease, less cost, and far greater validity. Tests at elevated and low temperatures are also more easily accomplished in this manner.

4.5.2 Puncture Resistance Tests

A representative construction shall be mounted in the specimen holder by pressing the retaining sleeve over the sample and main cylinder with sufficient force to prevent peripheral slippage during the test (Figure 46). A guided dart having a total weight of 5 pounds with an impacting blade conforming to Figure 46 shall be dropped onto the center of the test specimen parallel to the weakest weave direction, if such exists. The sample shall withstand a dart drop from a height based on the following equation:

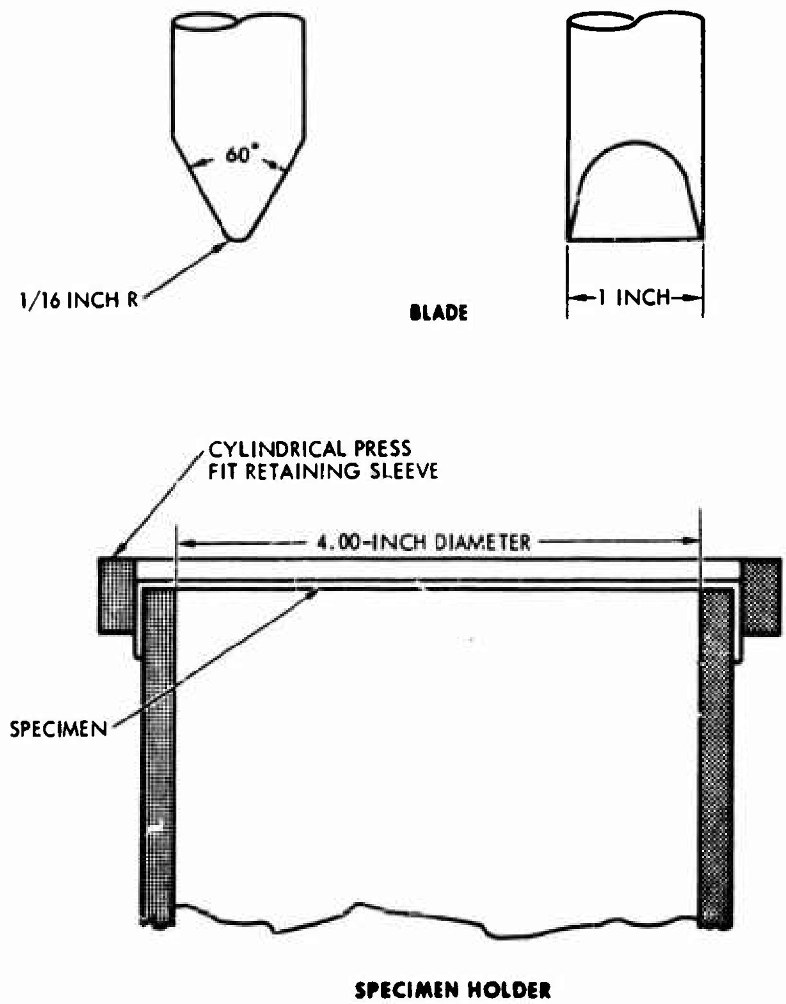


Figure 46. Puncture Test Blade and Specimen Holder, Type II, Classes A, B, and C Test.

$$H = 0.005\ S_u$$

where

H = height

S_u = ultimate strength (lb/in. width in weakest direction)

[redacted] [redacted]

4.5.3 Tear Resistance

A representative sample conforming to that shown in Figure 47 shall be mounted in a specimen holder similar to that shown in Figure 16. The same dart assembly used in the puncture tests (4.5.2) is used with a blade conforming to Figure 47. Total dart weight remains 5 pounds. The blade is dropped from a height of 20 feet, impacting the test sample at the base of the V. The resultant tear (D) will not exceed the figure set by the following equation:

$$D\ (\text{in.}) = 0.001\ S_u$$

where

S_u = ultimate strength (lb/in. width in weakest direction)

[redacted] [redacted]

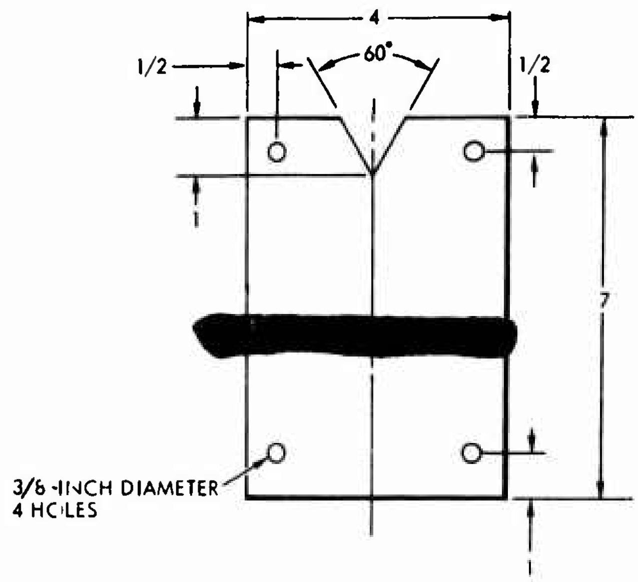
4.5.4 Qualitative Tank Drop Tests

Tanks being qualified for Phase II of MIL-T-6396 and MIL-T-27422 should be tested for crash resistance by the following drop tests.

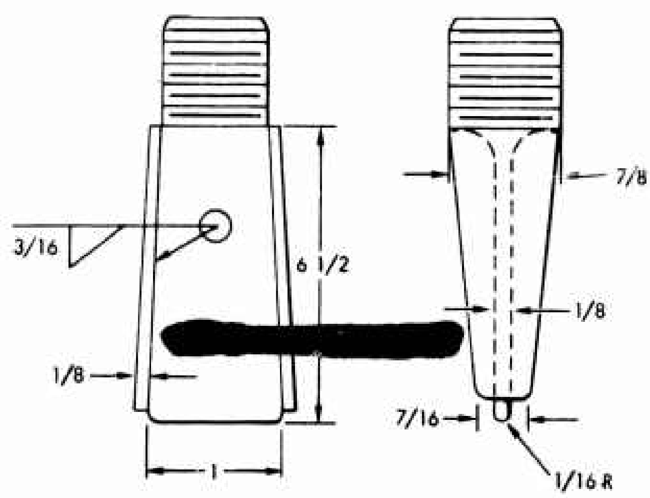
4.5.4.1 Anvil Impact Drop Test

Apparatus

The apparatus for this test is a 90-degree angle cone with an 8-inch-diameter base, the apex of the cone having a one-half-inch radius. The total height of the anvil should be 24 inches. The tank is supported by a rope sling. It is also



EDGEWISE TEAR SAMPLE



EDGEWISE TEAR BLADE

NOTE: ALL MEASUREMENTS ARE IN INCHES

Figure 47. Edgewise Tear Sample and Tear Blade.

supported on four sides by corrugated sheets whose edges are tacked together sufficiently to give the tank minimal support to maintain its shape under dead weight conditions (i.e., Kaiser diamond rib corrugated aluminum sheet, 0.031 inch thick, or equivalent), yet not capable of adding appreciably to the impact resistance of the cell. The impact side of the cell (i.e., that side with the greatest impact probability during a crash, as the tank bottom for helicopters) will remain exposed. Guide cables are used to stabilize the orientation of the tank as it drops.

Test Conditions

The test should be conducted at ambient temperatures ranging from 60 to 80 degrees F unless otherwise specified.

Testing

The test is conducted by hoisting the tank, filled to capacity with water, above the cone and aligning it to strike at the predetermined point of impact. The tank is then raised so that the impact side of the tank is 10 feet above the apex of the cone and released by an appropriate release mechanism. If failure occurs at any point, the tank would be rejected. Failure constitutes fluid loss in excess of 1 liter per minute.

4.5.4.2 Flat Impact Drop Test

Apparatus

The tank is supported by a rope sling in such a manner that the Z-axis of a helicopter tank or the X-axis of a wing tank is aligned with the direction of the drop. The tank is dropped onto a horizontal concrete slab. Guide cables are used to stabilize the orientation of the tank as it drops.

Test Conditions

The test should be conducted at ambient temperatures ranging from 60 to 80 degrees F unless otherwise specified.

Testing

The test is conducted by hoisting the tank, filled to capacity with water, to a height of 25 feet above the concrete slab. The tank is then released by an appropriate release mechanism. If failure occurs at any point, the tank would be rejected. Failure constitutes fluid loss in excess of 1 liter per minute.

APPENDIX II, CERTIFICATION OF OUTSIDE TESTS FOR FUNGUS RESISTANCE

REPORT

TRUESDAIL LABORATORIES, INC.

CHEMISTS - BACTERIOLOGISTS - ENGINEERS
RESEARCH — DEVELOPMENT — TESTING

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Arizona Division
Litchfield Park, Arizona Attn: Mr. R. L. Cook
Dept. 452

DATE December 6, 1965

RECEIVED October 28, 1965

LABORATORY NO. 73863

SAMPLE Forty 1" x 8" x .025"
Laminate Specimens (4 lots of 10 replicates each)
Marked: as shown
P.O. No. 108597-X

INVESTIGATION

Fungus resistance as defined by MIL-STD 810A (USAF) Method 508.1, for U. S. Government Contract DA-440177-AMC-347(T).

RESULTS

Lot Designation	Number of Replicates	FUNGUS RESISTANCE TEST* (30°C/28 days) Visual Inspection
W7	10	No mold growth or evidence of deterioration of specimen.
X7	10	No mold growth or evidence of deterioration of specimen.
Y7	10	No mold growth or evidence of deterioration of specimen.
Z11	10	No mold growth or evidence of deterioration of specimen.

*Mixed spore suspension of: Chaetomium globosum ATCC 6205
Aspergillus niger ATCC 6275
Aspergillus tamarii (A. [illegible]) ATCC 10836
Penicillium ochrochloron ATCC 9112

CONCLUSIONS

The results indicate that all the laminate specimens submitted possess sufficient fungus resistance as specified by Military Specification MIL-STD 810A (USAF) Method 508.1.

Respectfully submitted,

TRUESDAIL LABORATORIES, INC.

C. E. P. Jeffreys

C.E.P. Jeffreys, Ph. D.
Technical Director

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13. ABSTRACT

Basic physical tests pertaining to Specifications MIL-T-6396 and T-27422 were performed on Goodyear Aerospace developed materials, coded ARM-018 and ARM-021. These tests were conducted first on the ARM-018 to substantiate and document the improved performance shown by this material in earlier laboratory tests and actual aircraft crashes. Material failure mechanics under a variety of static and dynamic loading conditions were included to accurately simulate and measure crash performance. (U)

As the test series progressed, some deficiencies were discovered in the ARM-018 material. These included low dynamic puncture and tear resistance. A careful analysis of the problem area led to changes in material processing, and the resultant composition was given the code name ARM-021. Although the basic ingredients remained the same, this modification of material showed great superiority over the ARM-018 in both puncture and tear resistance. Because of the considerable improvement of the ARM-021 material over conventional crash-resistant materials and because of deficiencies in test standards of crash resistance found in MIL-T-27422, changes in this specification have been suggested. (U)

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Crash-Resistant Fuel Cells						
Energy Absorbing Materials						
Dynamic Testing						

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